MiniBooNE, a neutrino oscillation experiment at Fermilab

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Massachusetts Institute of Technology
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Outline

1. Introduction
2. Neutrino beam
3. Events in the detector
4. Cross section model
5. Oscillation analysis and result
6. New Low energy excess result
7. Anti-neutrino oscillation result
8. Neutrino disappearance result
9. Outlook

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1. Neutrino oscillation

The neutrino weak eigenstate is described by neutrino Hamiltonian eigenstates, ν_1, ν_2, and ν_3 and their mixing matrix elements.

$$|\nu_e\rangle = \sum_{i=1}^{3} U_{ei} |\nu_i\rangle$$

The time evolution of neutrino weak eigenstate is written by Hamiltonian mixing matrix elements and eigenvalues of ν_1, ν_2, and ν_3.

$$|\nu_e(t)\rangle = \sum_{i=1}^{3} U_{ei} e^{-i\lambda_i t} |\nu_i\rangle$$

Then the transition probability from weak eigenstate ν_μ to ν_e is (no CP violation)

$$P_{\mu\to e}(t) = \left|\langle \nu_e(t) | \nu_\mu \rangle\right|^2 = -4 \sum_{i>j} \left(U_{\mu i} U_{\mu j} U_{ei} U_{ej} \right) \sin^2\left(\frac{\Delta_{ij}}{2} t \right)$$

So far, model independent

1. Neutrino oscillation

From here, model dependent formalism.
In the vacuum, 2 neutrino state effective Hamiltonian has a form,

$$H_{eff} \rightarrow \begin{pmatrix} \frac{m_{ee}^2}{2E} & \frac{m_{e\mu}^2}{2E} \\ \frac{m_{e\mu}^2}{2E} & \frac{m_{\mu\mu}^2}{2E} \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \frac{m_1^2}{2E} & 0 \\ 0 & \frac{m_2^2}{2E} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Therefore, 2 massive neutrino oscillation model is

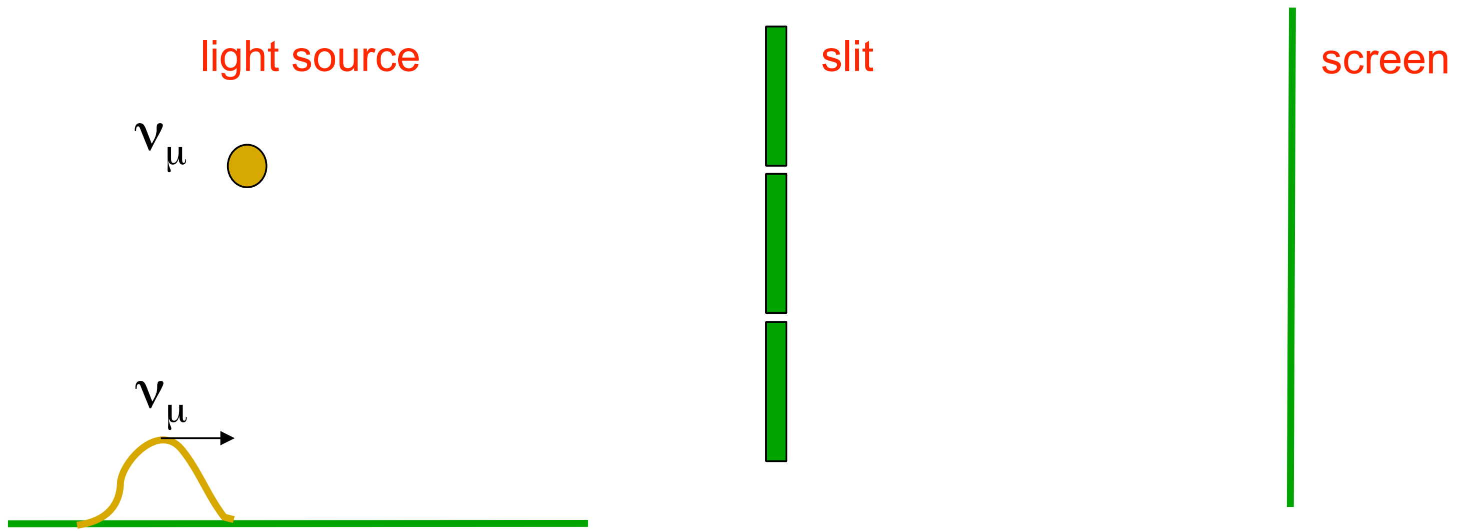
$$P_{\mu\rightarrow e}(t) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} t\right)$$

Or, conventional form

$$\boxed{P_{\mu\rightarrow e}(L/E) = \sin^2 2\theta \sin^2\left(1.27\Delta m^2(eV^2)\frac{L(m)}{E(MeV)}\right)}$$

1. Neutrino oscillation

Neutrino oscillation is an interference experiment (cf. double slit experiment)



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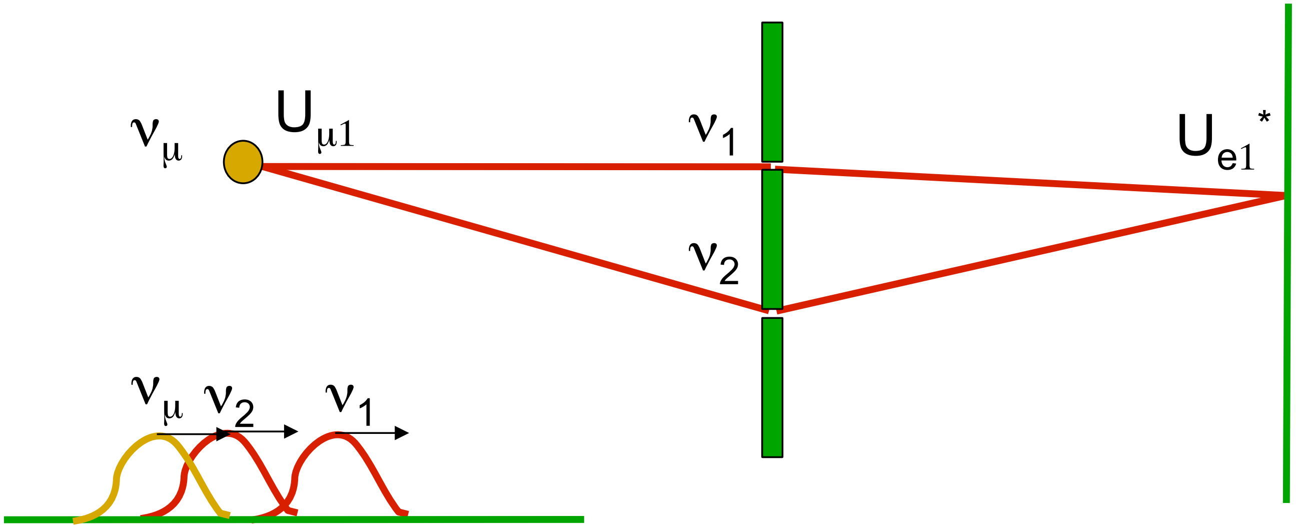

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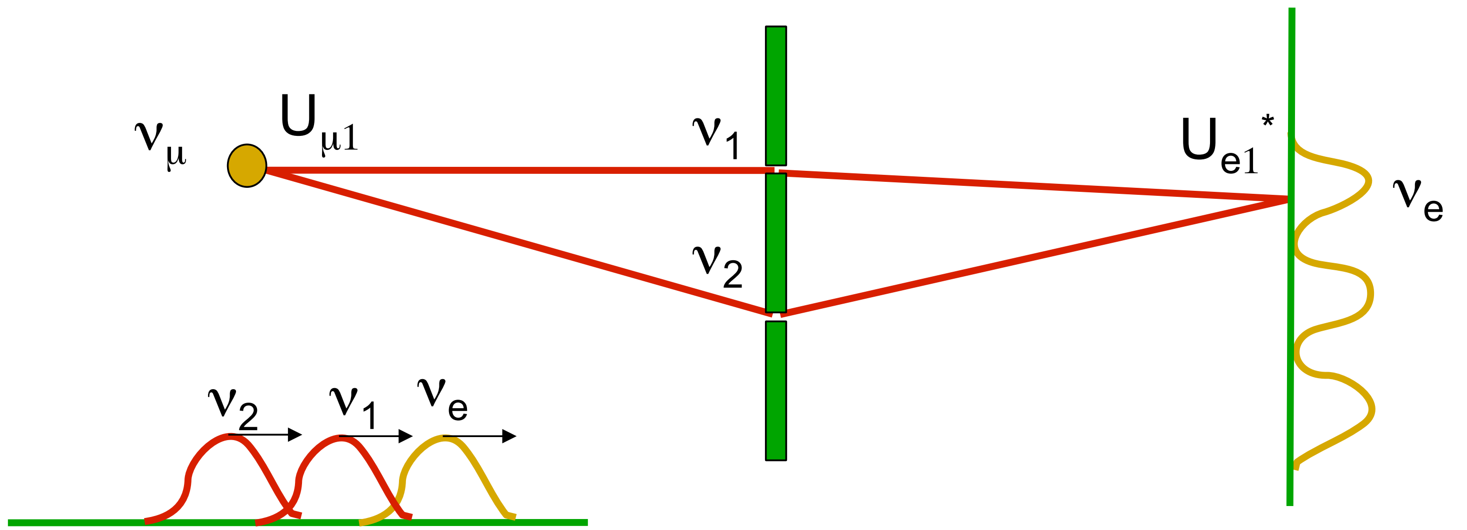

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LSND Collaboration,
PRD 64, 112007

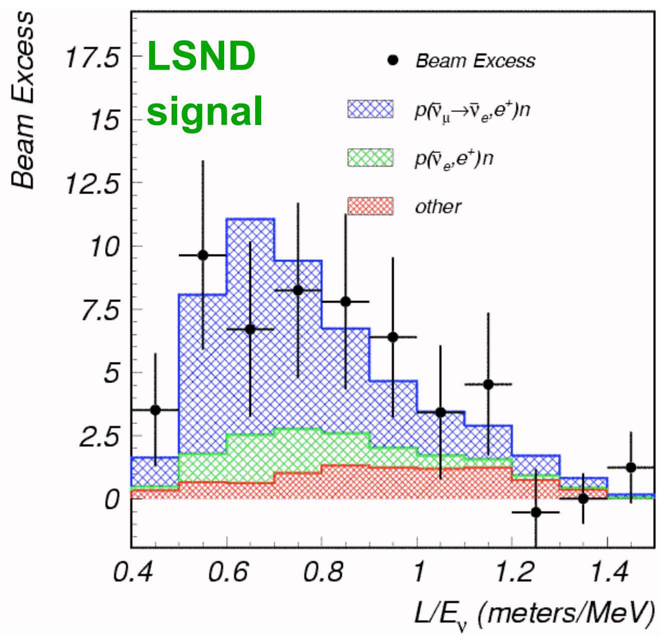
1. LSND experiment

LSND experiment at Los Alamos observed excess of anti-electron neutrino events in the anti-muon neutrino beam.

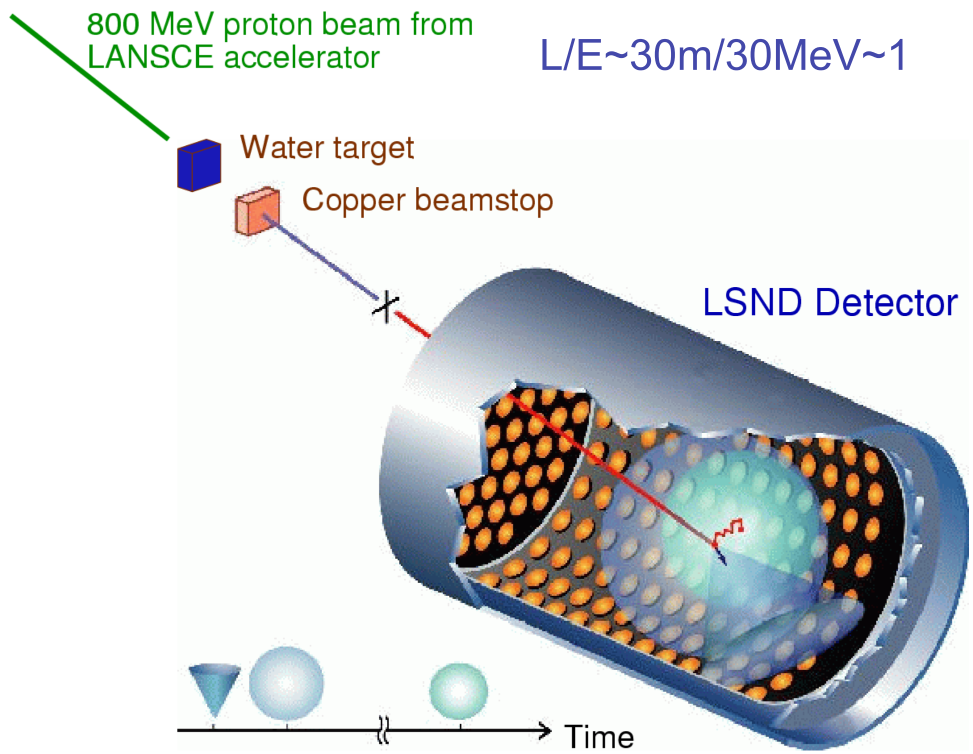
$$\bar{\nu}_\mu \xrightarrow{oscillation} \bar{\nu}_e + p \rightarrow e^+ + n$$

$$n + p \rightarrow d + \gamma$$

87.9 ± 22.4 ± 6.0 (3.8.σ)



L/E~30m/30MeV~1



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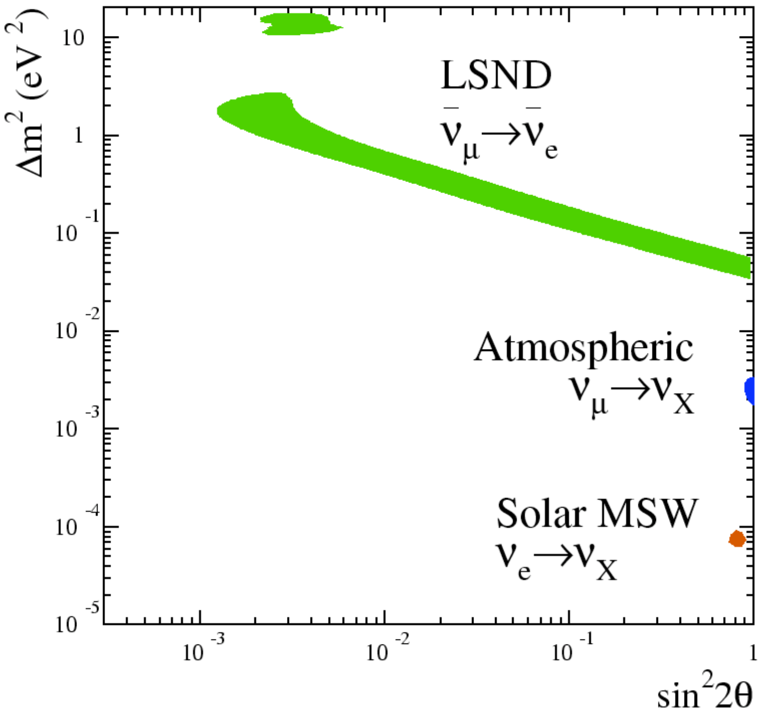
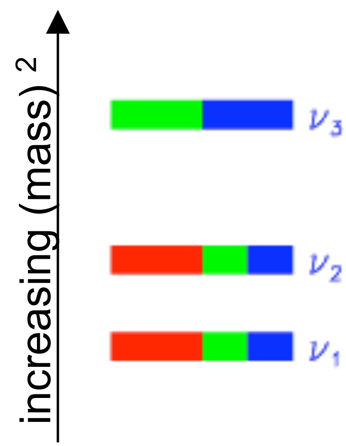


3 types of neutrino oscillations are found:

LSND neutrino oscillation: $\Delta m^2 \sim 1 eV^2$
Atmospheric neutrino oscillation: $\Delta m^2 \sim 10^{-3} eV^2$
Solar neutrino oscillation : $\Delta m^2 \sim 10^{-5} eV^2$

But we cannot have so many Δm^2!

$$\Delta m_{13}^2 \neq \Delta m_{12}^2 + \Delta m_{23}^2$$



We need to test LSND signal

MiniBooNE experiment is designed to have same L/E~500m/500MeV~1 to test LSND $\Delta m^2 \sim 1 eV^2$

1. MiniBooNE experiment

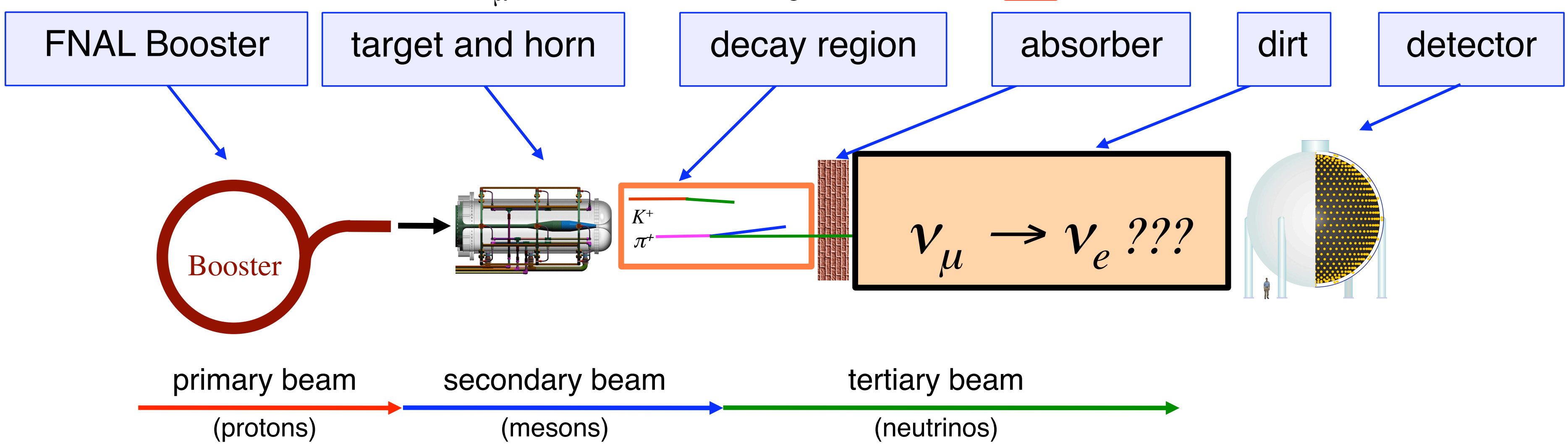
Keep L/E same with LSND, while changing systematics, energy & event signature;

$P(\nu_\mu - \nu_e) = \sin^2 2\theta \, \sin^2(1.27 \Delta m^2 L/E)$

MiniBooNE is looking for the single isolated electron like events, which is the signature of ν_e events

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \rightarrow p + \boxed{e^-}$$

$$\bar{\nu}_\mu \xrightarrow{\text{oscillation}} \bar{\nu}_e + p \rightarrow n + \boxed{e^+}$$



MiniBooNE has;

- higher energy (~500 MeV) than LSND (~30 MeV)
- longer baseline (~500 m) than LSND (~30 m)

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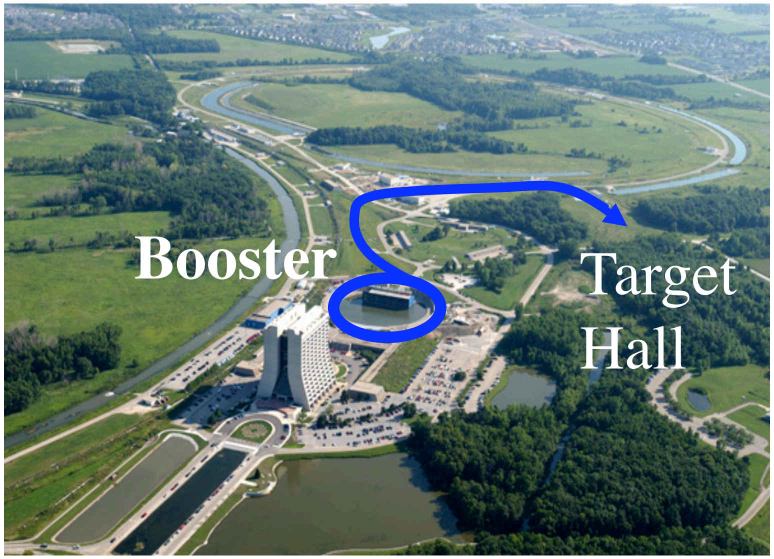
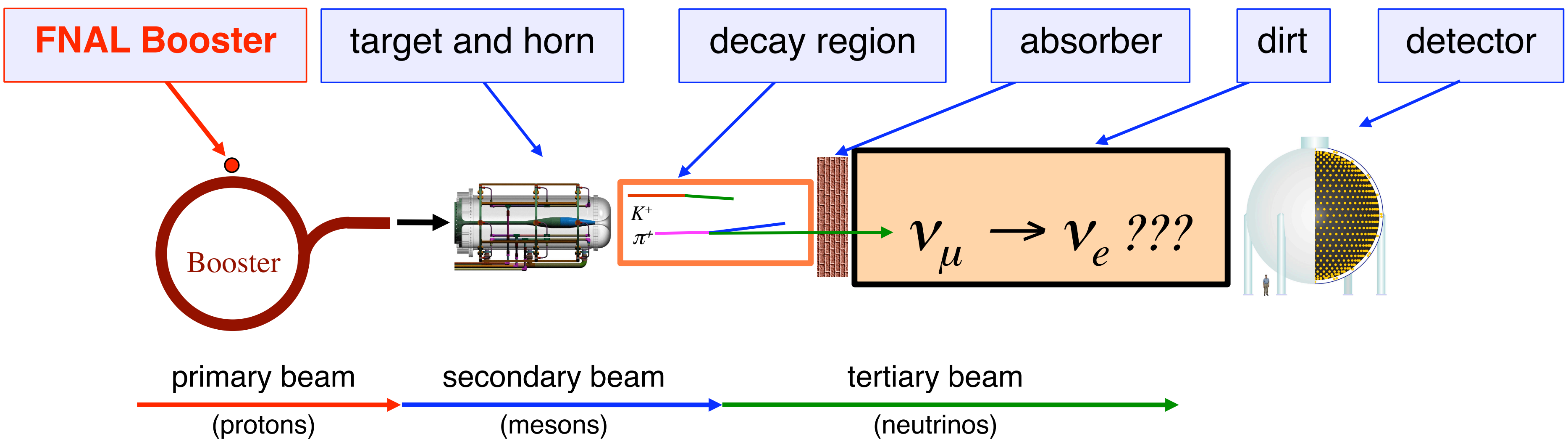
MiniBooNE collaboration,
PRD79(2009)072002

2. Neutrino beam



MiniBooNE extracts beam from the 8 GeV Booster



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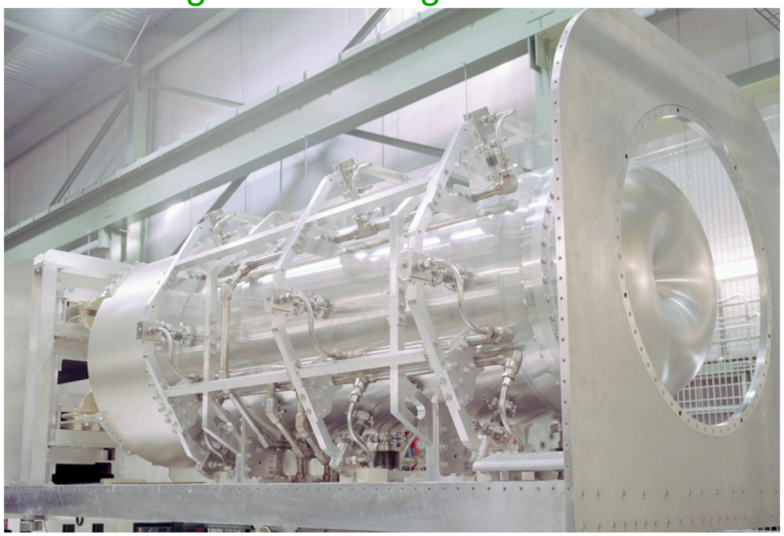
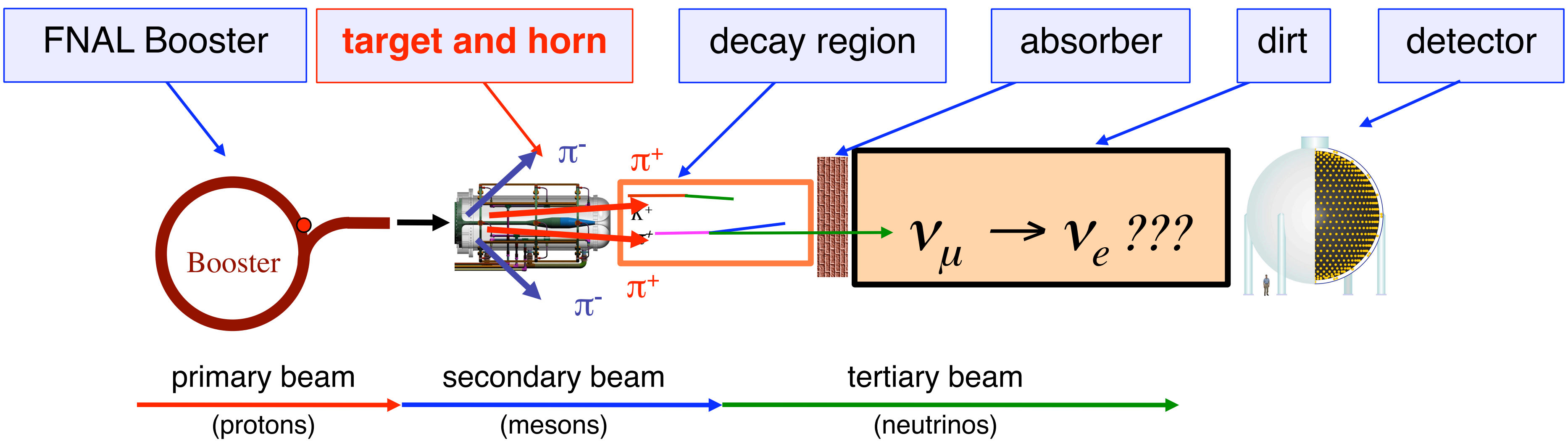
2. Neutrino beam

Magnetic focusing horn



8GeV protons are delivered to a 1.7 λ Be target

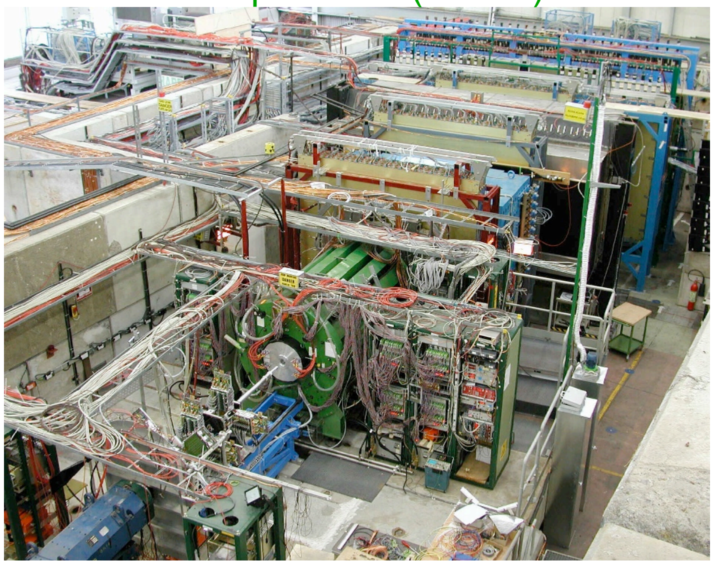
within a magnetic horn (2.5 kV, 174 kA) that increases the flux by $\times$ 6



MiniBooNE collaboration,
PRD79(2009)072002

2. Neutrino beam

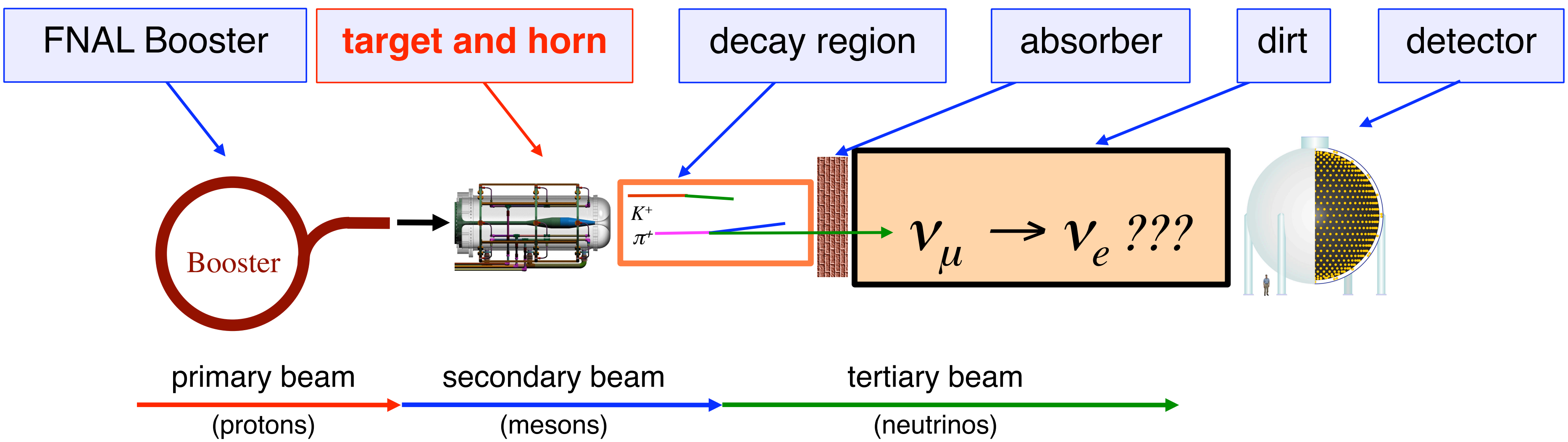
HARP experiment (CERN)



Modeling of meson production is based on the measurement done by HARP collaboration.

HARP collaboration,
Eur.Phys.J.C52(2007)29

- Identical, but 5% λ Beryllium target
- 8.9 GeV/c proton beam momentum



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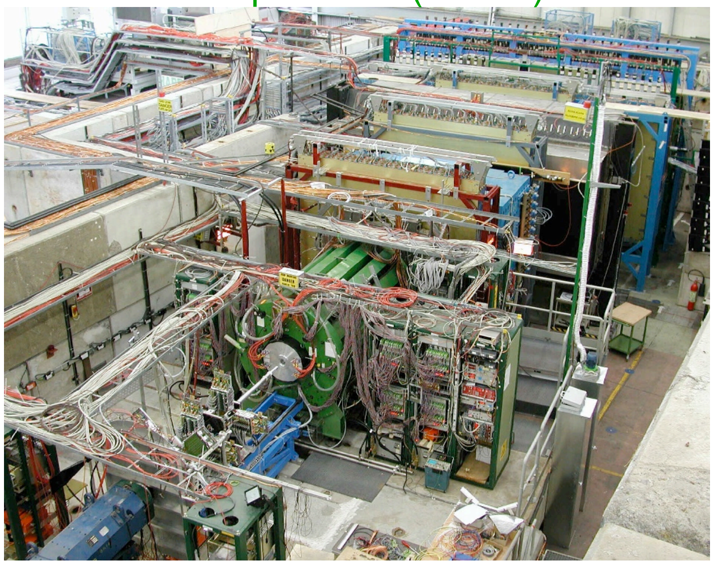

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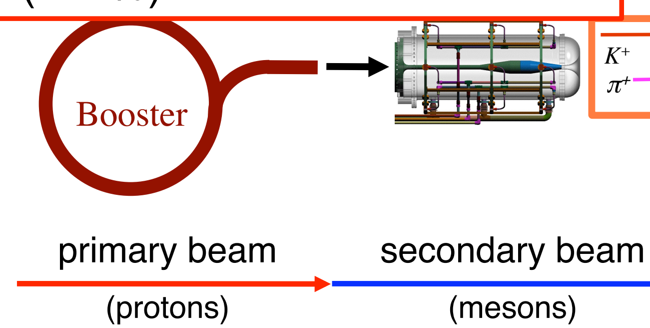
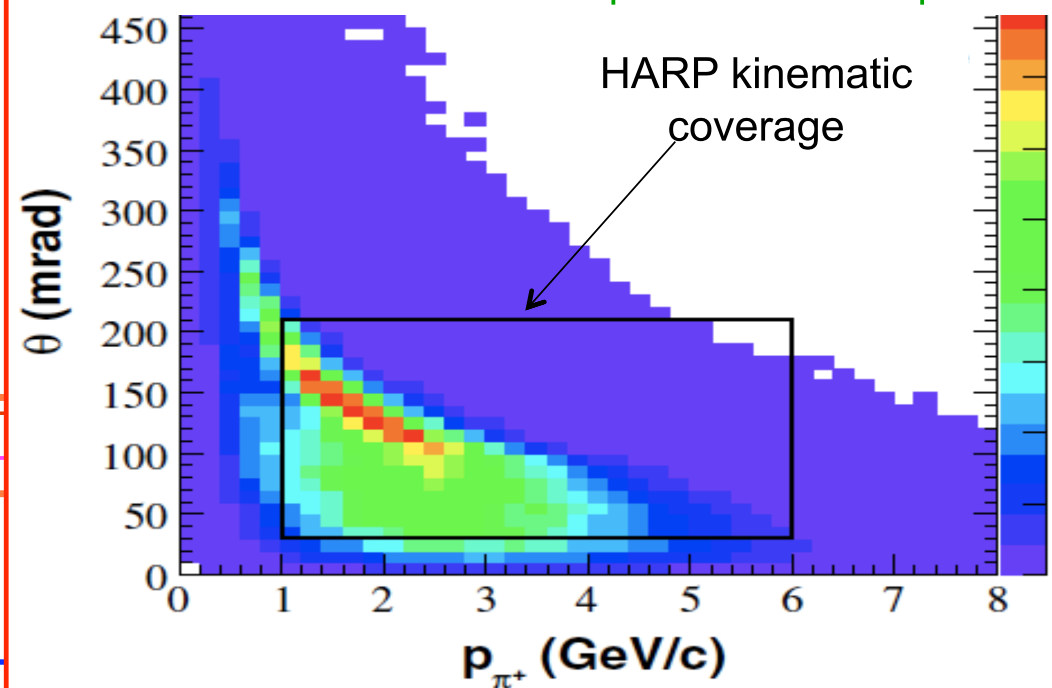
Majority of pions create neutrinos in MiniBooNE are directly measured by HARP (>80%)



Booster neutrino beamline pion kinematic space



MiniBooNE collaboration,
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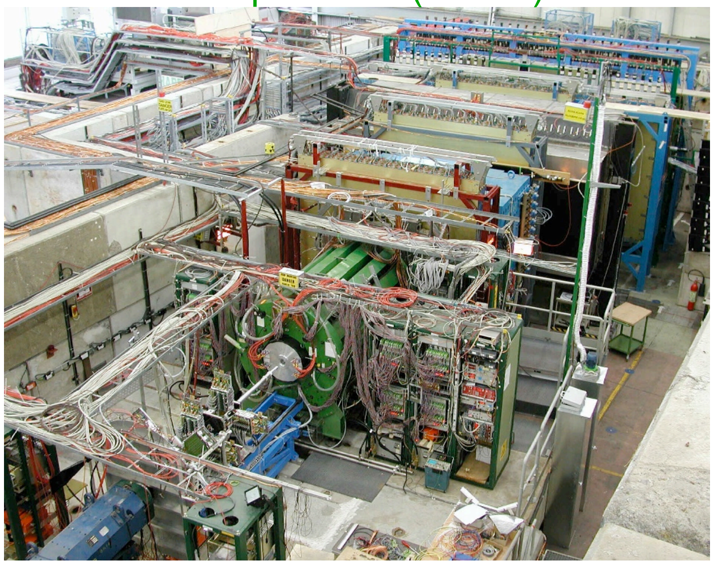

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HARP collaboration,
Eur.Phys.J.C52(2007)29

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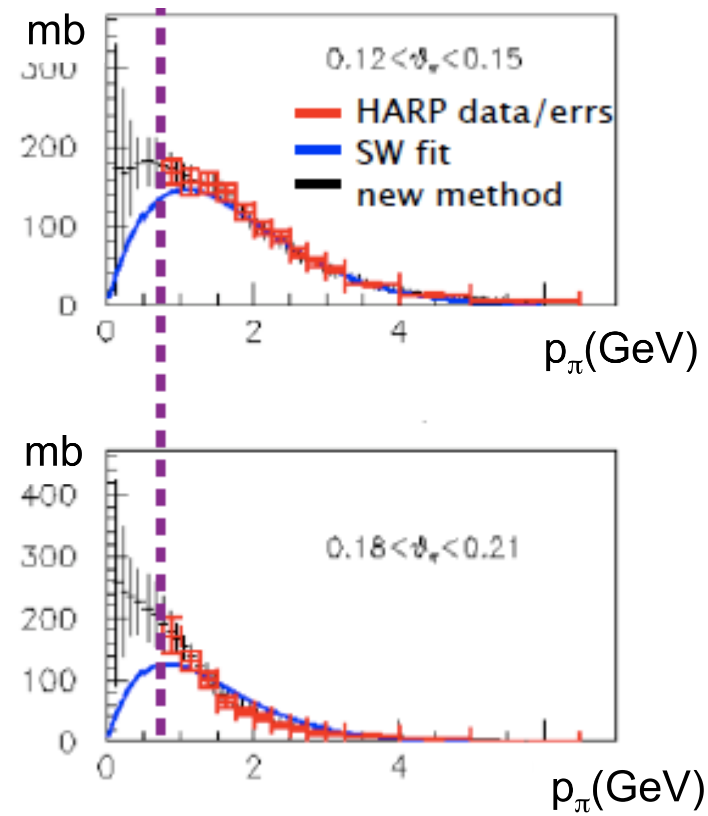
HARP data with 8.9 GeV/c proton beam momentum

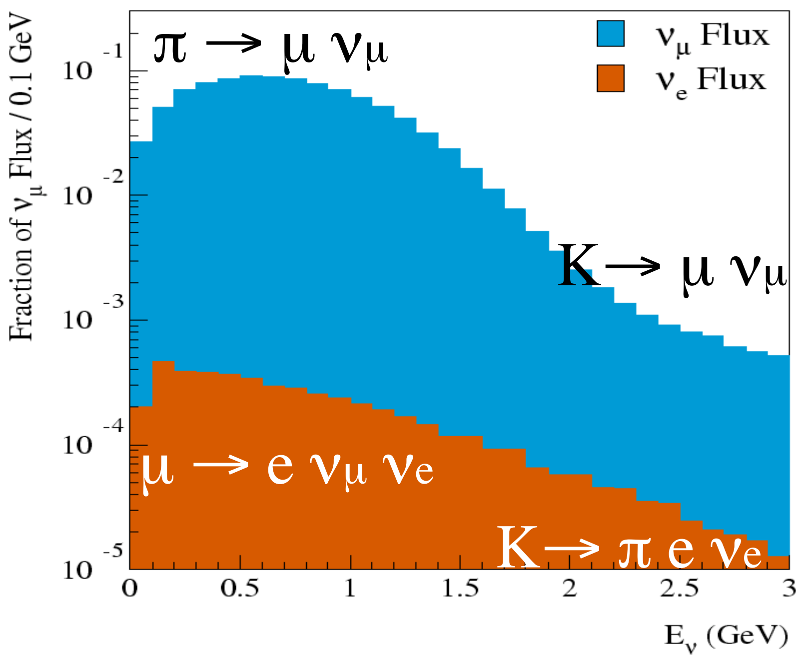


Majority of pions create neutrinos in MiniBooNE are directly measured by HARP (>80%)

The error on the HARP data (~7%) directly propagates.
The neutrino flux error is the dominant source of normalization error for an absolute cross section in MiniBooNE, however it doesn't affect oscillation analysis.

MiniBooNE collaboration,
PRD79(2009)072002

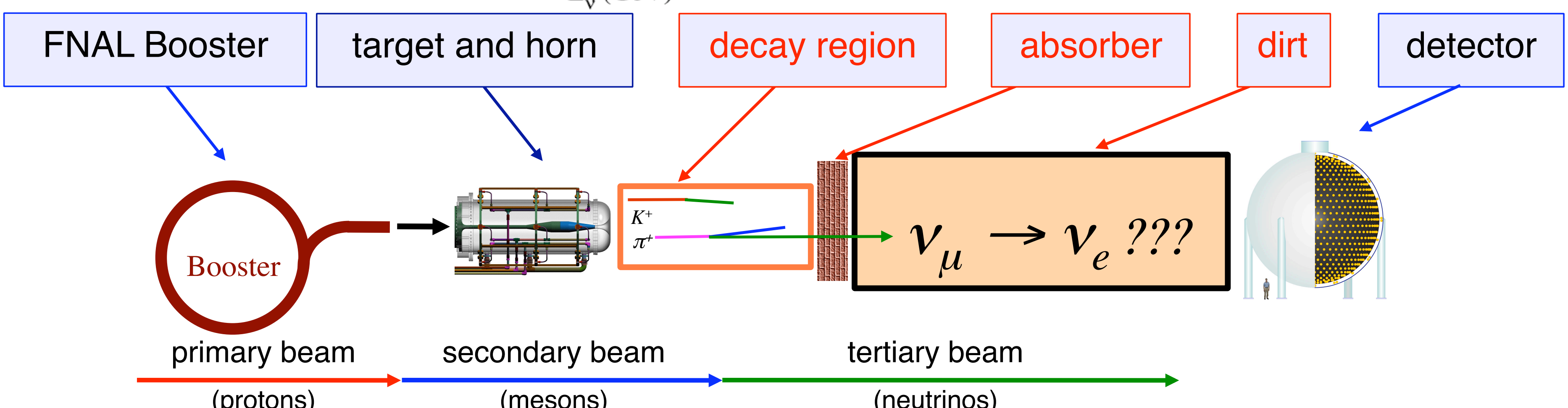
2. Neutrino beam



Neutrino flux from simulation by GEANT4

MiniBooNE is the ν_e (anti ν_e) appearance oscillation experiment, so we need to know the distribution of beam origin ν_e and anti ν_e (intrinsic ν_e)

	neutrino mode	antineutrino mode
intrinsic ν_e contamination	0.6%	0.6%
intrinsic ν_e from μ decay	49%	55%
intrinsic ν_e from K decay	47%	41%
wrong sign fraction	6%	16%



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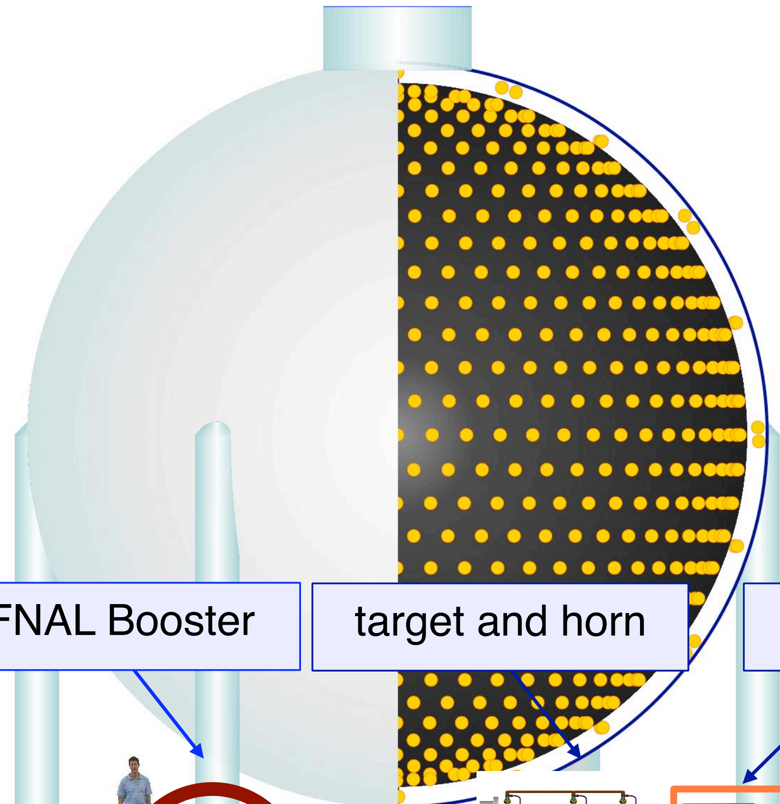
MiniBooNE collaboration,
NIM.A599(2009)28

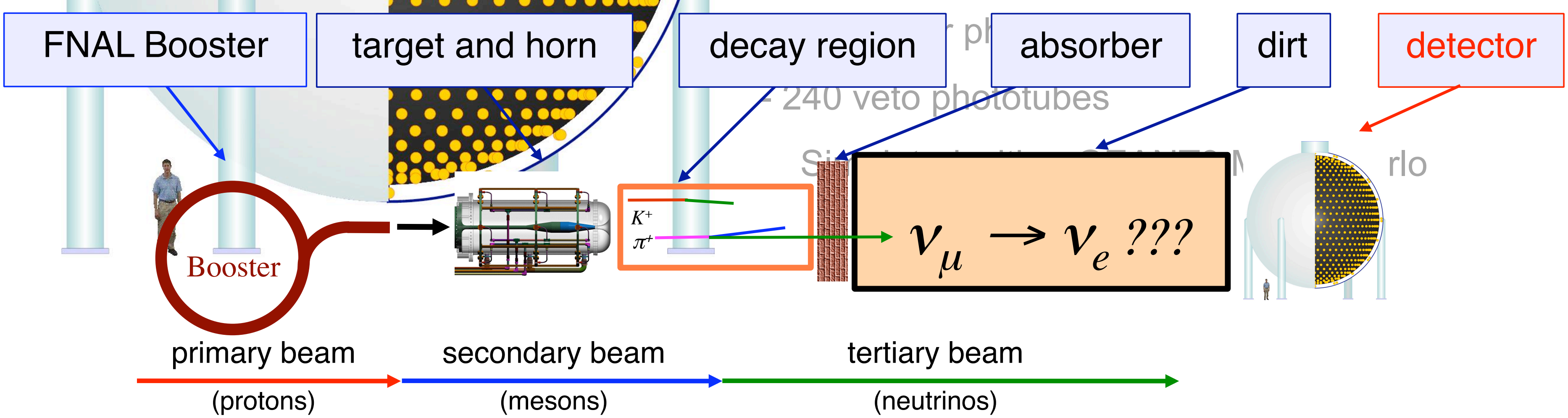
3. Events in the Detector



The MiniBooNE Detector

- 541 meters downstream of target
- 3 meter overburden
- 12 meter diameter sphere
  (10 meter “fiducial” volume)
- Filled with 800 t of pure mineral oil (CH_2)
  (Fiducial volume: 450 t)
- ... r pl...
- 240 veto phototubes

Si... rlo



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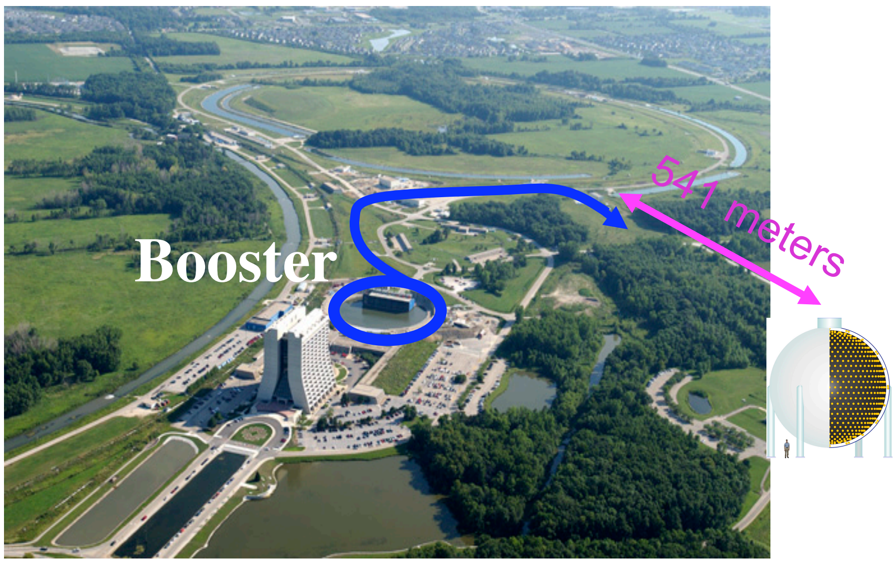

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  Simulated with a GEANT3 Monte Carlo

MiniBooNE collaboration,
NIM.A599(2009)28

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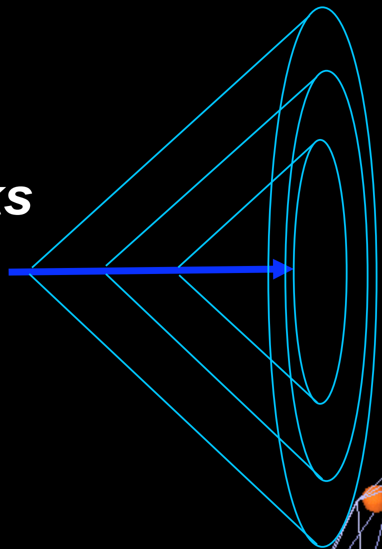
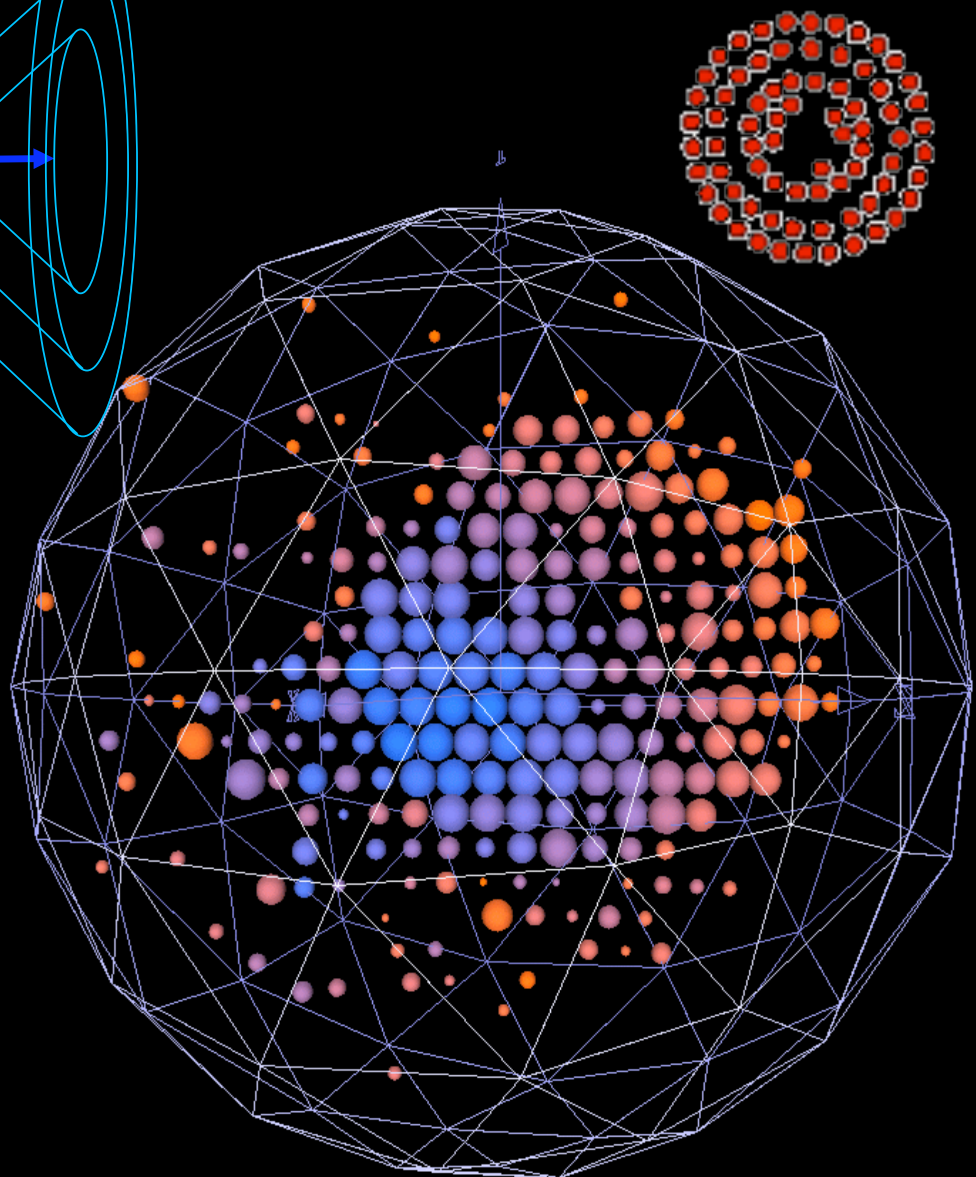
3. Events in the Detector

MiniBooNE collaboration, NIM.A599(2009)28

- ***Muons***
  - ***Sharp, clear rings***
    - ***Long, straight tracks***
- Electrons
  - Scattered rings
    - Multiple scattering
    - Radiative processes
- Neutral Pions
  - Double rings
    - Decays to two photons





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MiniBooNE collaboration, NIM.A599(2009)28

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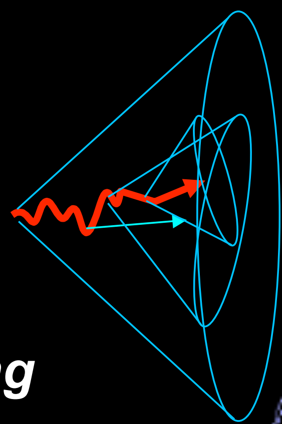

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MiniBooNE collaboration, NIM.A599(2009)28

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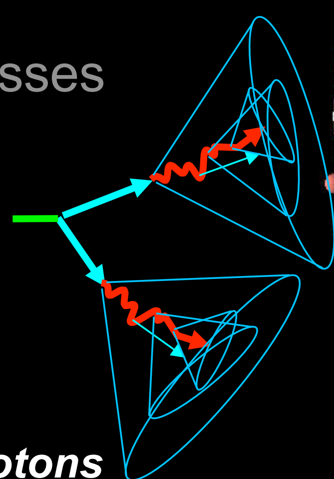

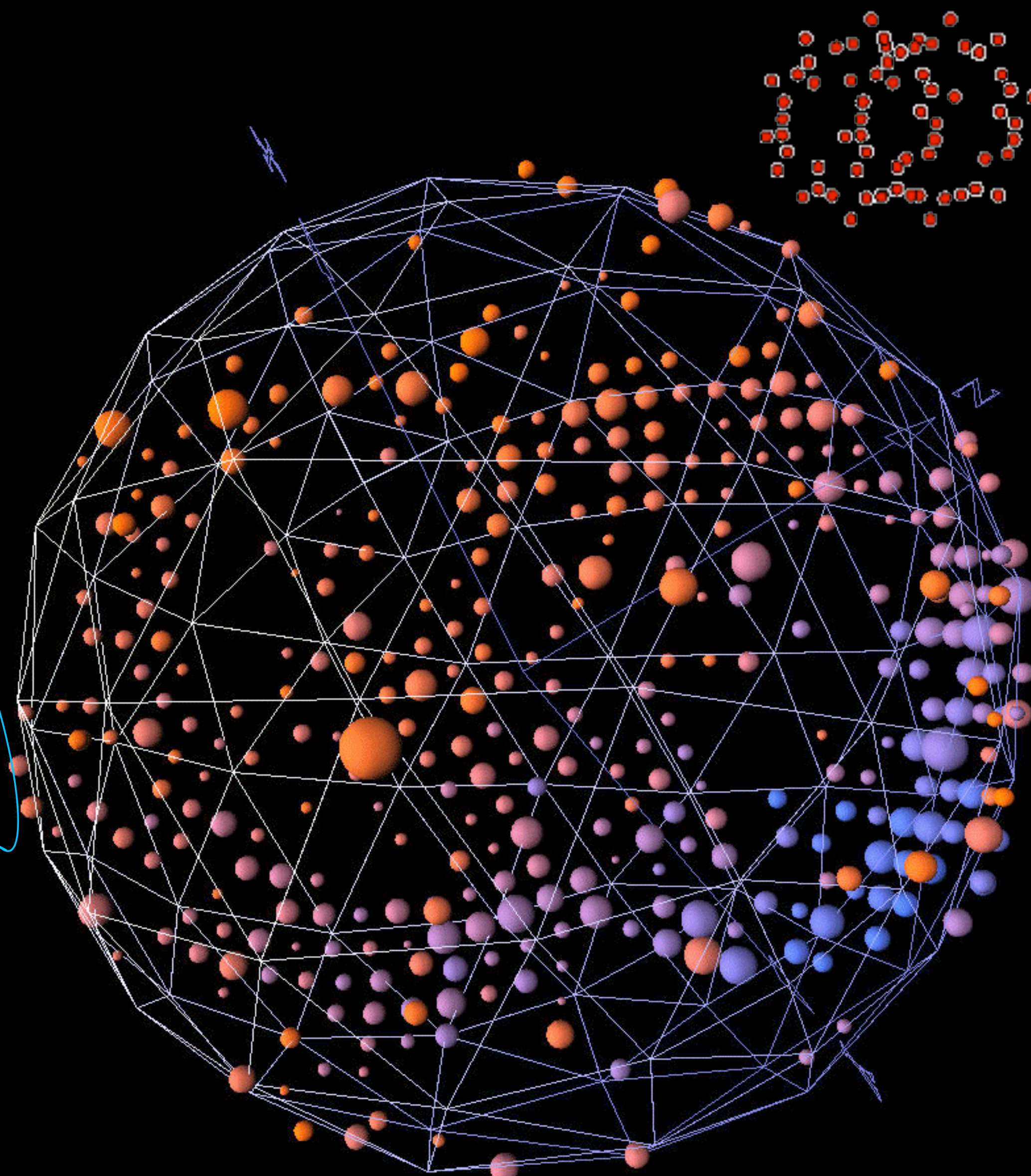

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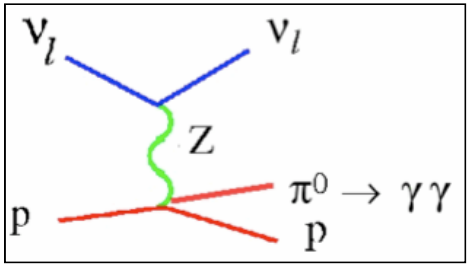
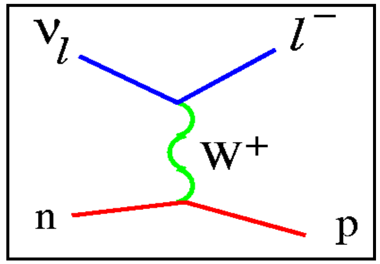
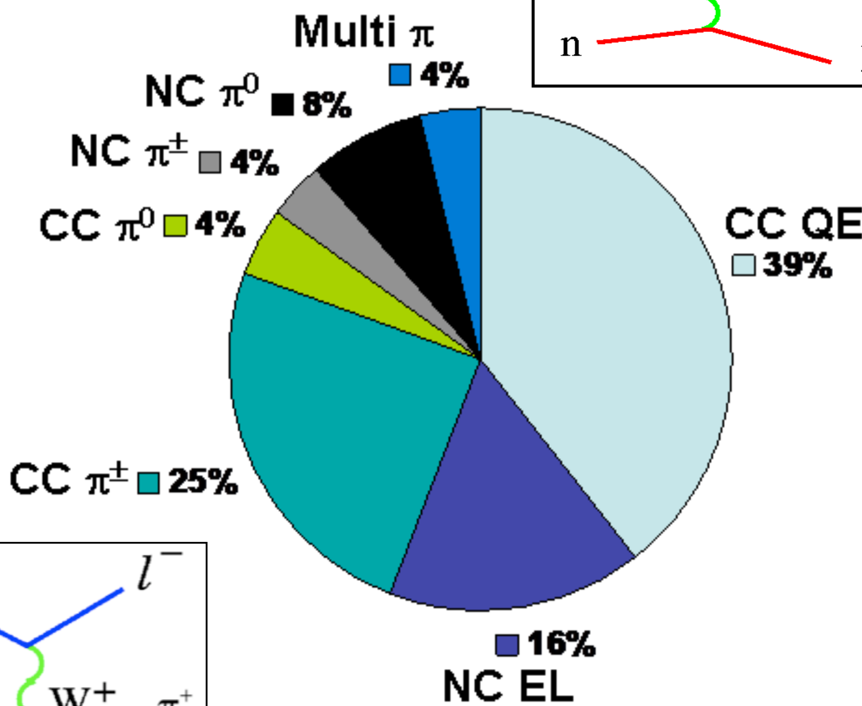
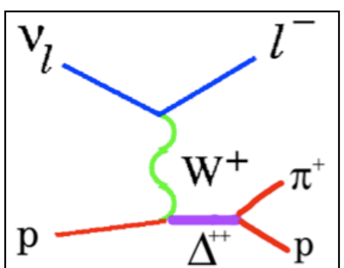


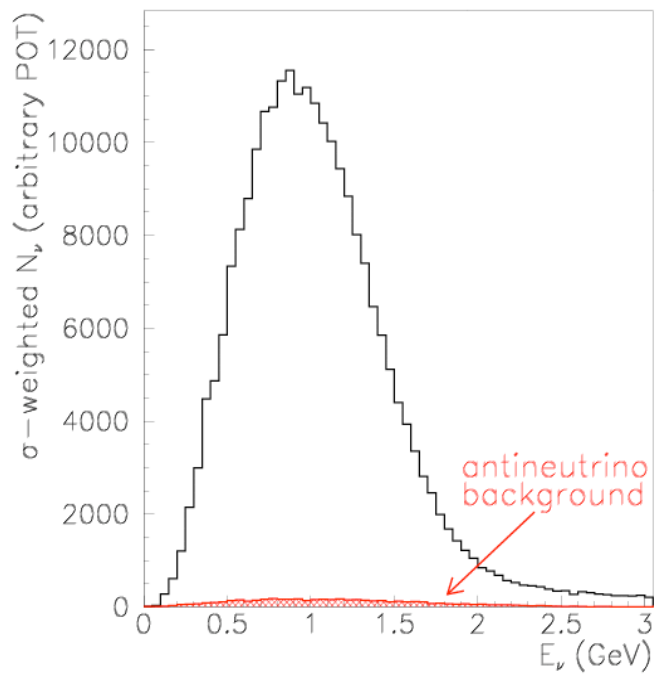






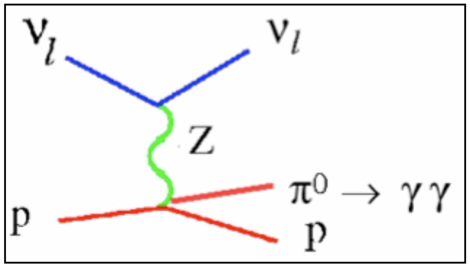
Predicted event rates before cuts (NUANCE Monte Carlo)

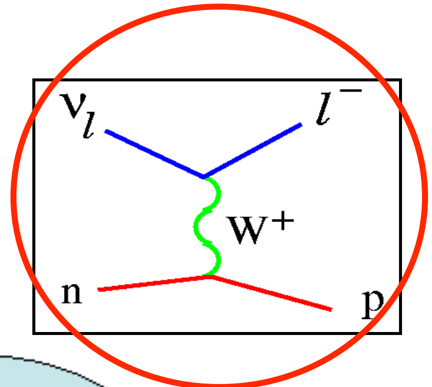
Casper, Nucl.Phys.Proc.Suppl.112(2002)161



Event neutrino energy (GeV)

4. Cross section model





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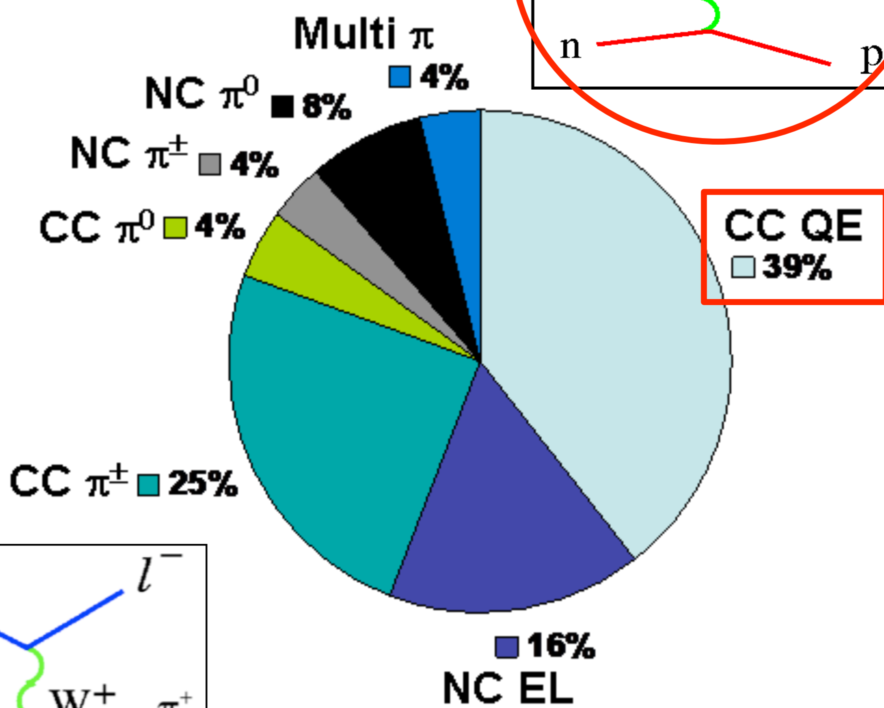

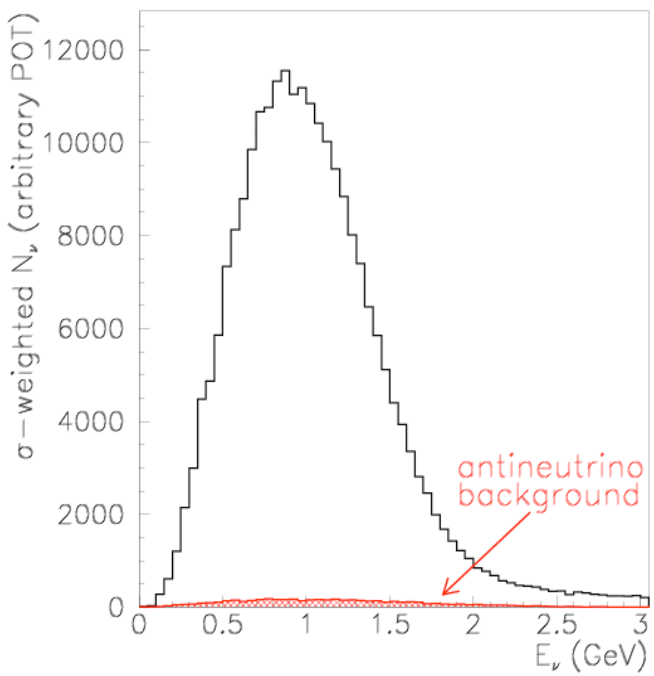

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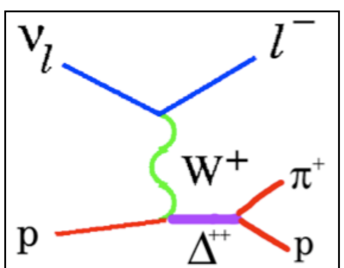


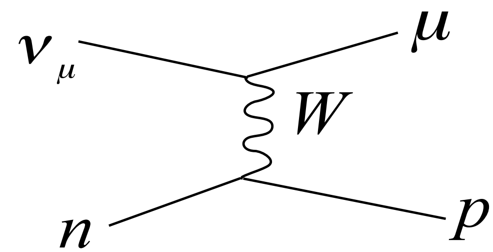
4. CCQE event measurement

CCQE (Charged Current Quasi-Elastic) event

ν_μ charged current quasi-elastic (ν_μ CCQE) interaction is the most abundant (~40%) and the fundamental interaction in MiniBooNE detector

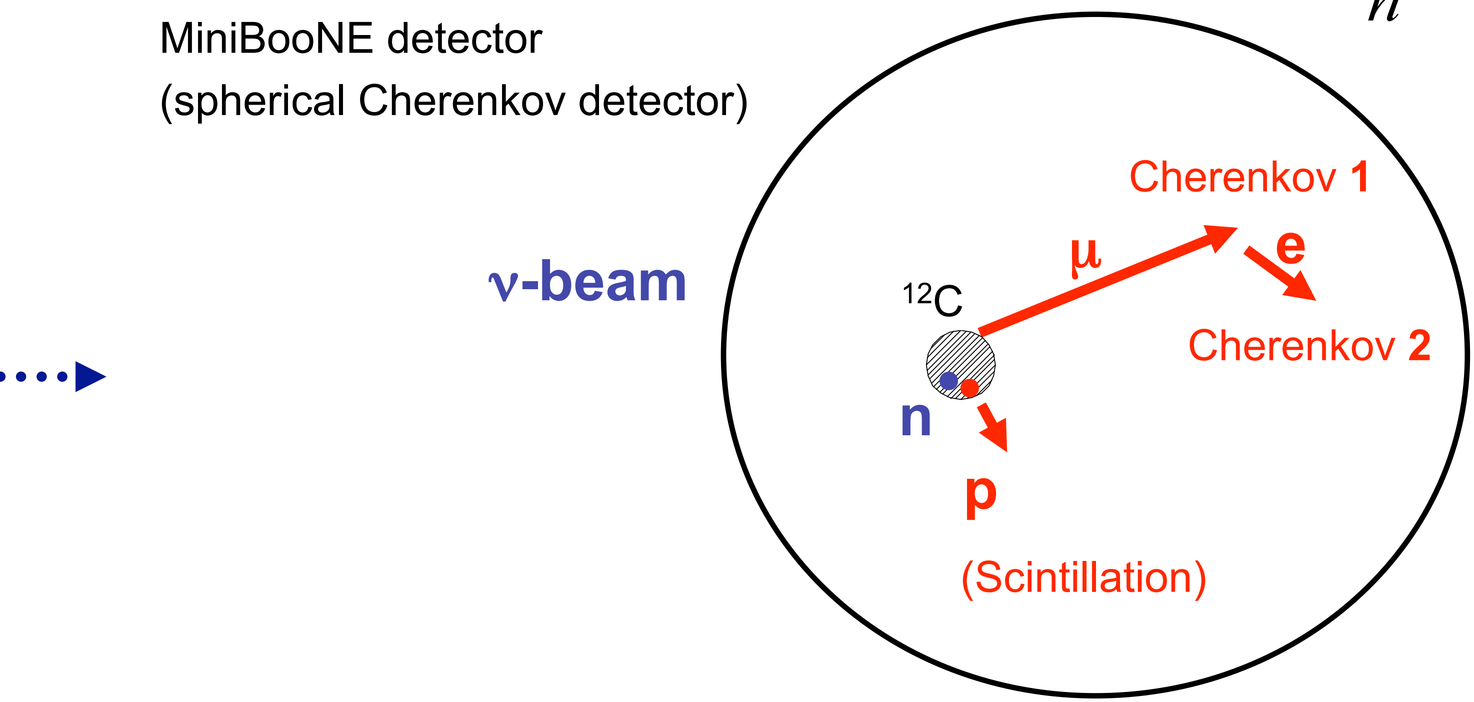
$$\nu_\mu + n \rightarrow p + \mu^-$$

$$(\nu_\mu + {}^{12}C \rightarrow X + \mu^-)$$



MiniBooNE detector

(spherical Cherenkov detector)



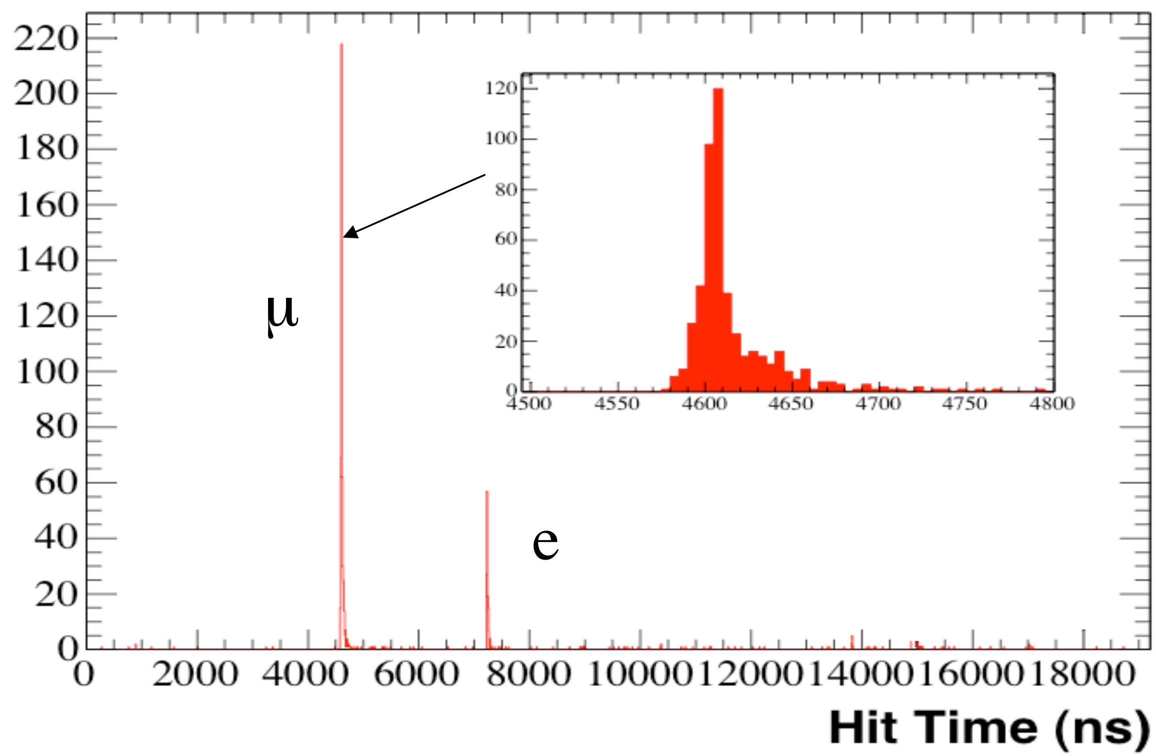
muon like Cherenkov light and subsequent decayed electron (Michel electron) like Cherenkov light are the signal of CCQE event

4. CCQE event measurement

19.2 μs beam trigger window with the 1.6 μs spill
Multiple hits within a ~100 ns window form “subevents”

ν_μ CCQE interactions (ν+n → μ+p) with characteristic two “subevent” structure from stopped $\mu \to \nu_\mu \nu_e e$

Number of tank hits for CCQE event



4. CCQE event measurement

All kinematics are specified from 2 observables, muon energy E_μ and muon scattering angle θ_μ

Energy of the neutrino E_ν^{QE} and 4-momentum transfer Q_2^{QE} can be reconstructed by these 2 observables, under the assumption of CCQE interaction with bound neutron at rest ("QE assumption"). CCQE is the signal channel of ν_e candidate.

$$E_\nu^{QE} = \frac{2(M - E_B)E_\mu - (E_B^2 - 2ME_B + m_\mu^2 + \Delta M^2)}{2[(M - E_B) - E_\mu + p_\mu \cos\theta_\mu]}$$

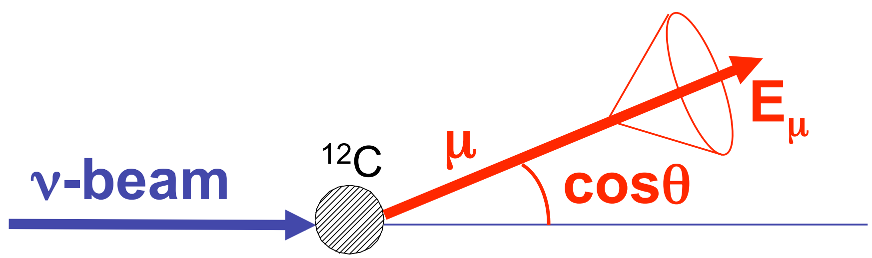
$$Q_{QE}^2 = -m_\mu^2 + 2E_\nu^{QE}(E_\mu - p_\mu \cos\theta_\mu)$$

$$\nu_\mu + n \to p + \mu^-$$

$$(\nu_\mu + {}^{12}C \to X + \mu^-)$$

$$\nu_e + n \to p + e^-$$

$$(\nu_e + {}^{12}C \to X + e^-)$$



Smith and Moniz,
Nucl.,Phys.,B43(1972)605

4. Relativistic Fermi Gas (RFG) model

Relativistic Fermi Gas (RFG) Model

Carbon is described by the collection of incoherent Fermi gas particles. All details come from hadronic tensor.

$$(W_{\mu\nu})_{ab} = \int_{Elo}^{Ehi} f(\vec{k},\vec{q},w) T_{\mu\nu} dE \text{ : hadronic tensor}$$

$$f(\vec{k},\vec{q},w) \text{ : nucleon phase space density function}$$

$$T_{\mu\nu} = T_{\mu\nu}(F_1, F_2, F_A, F_P) \text{ : nucleon tensor}$$

$$F_A(Q^2) = g_A / (1 + Q^2 / \boxed{M_A^2})^2 \text{ : Axial form factor}$$

$$Ehi \text{ : the highest energy state of nucleon } = \sqrt{(p_F^2 + M^2)}$$

$$Elo \text{ : the lowest energy state of nucleon } = \boxed{\kappa}\left(\sqrt{(p_F^2 + M^2)} - \omega + E_B\right)$$

We tuned following 2 parameters using Q^2 distribution by least χ^2 fit;

M_A = effective axial mass

κ = Pauli blocking parameter

MiniBooNE collaboration
PRL100(2008)032301

4. CCQE cross section model tuning

The data-MC agreement in Q^2 (4-momentum transfer) is not good
We tuned nuclear parameters in Relativistic Fermi Gas model

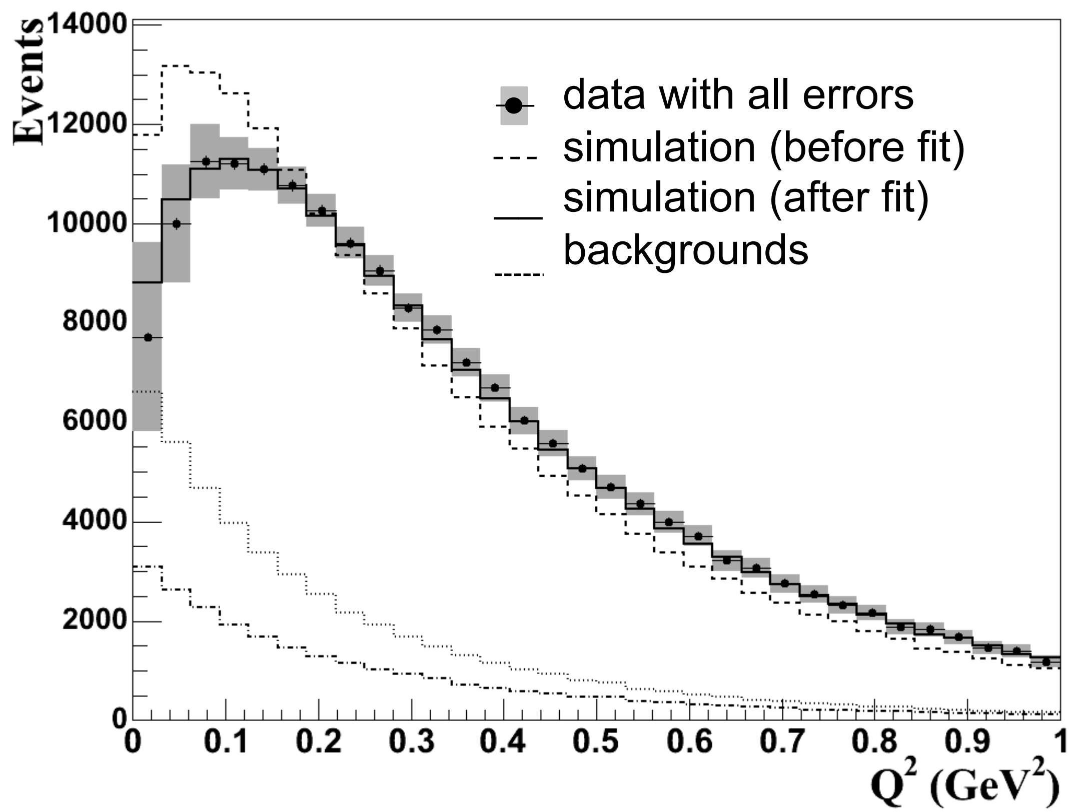
Q^2 fits to MB ν_μ CCQE data using the nuclear parameters:

M_A^{eff} - effective axial mass
κ - Pauli Blocking parameter

Relativistic Fermi Gas Model with tuned parameters describes ν_μ CCQE data well

This improved nuclear model is used in ν_e CCQE model, too.

Q^2 distribution before and after fitting

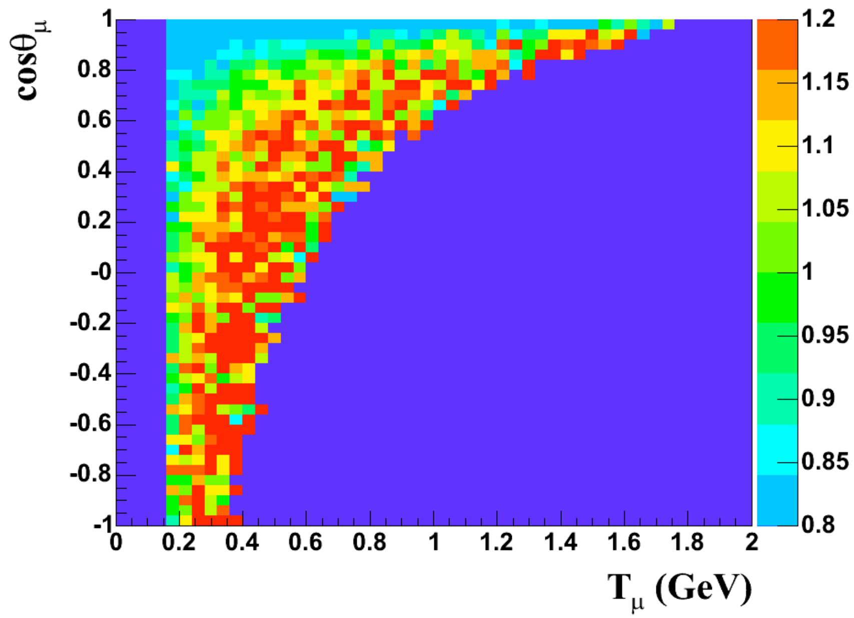


4. CCQE cross section model tuning

Without knowing flux perfectly, we cannot modify cross section model

$$R(\mathrm{interaction}) \propto \int (\mathrm{flux}) \times (\mathrm{xs})$$

Data-MC ratio for T_μ-$\cos\theta_\mu$ plane, before tuning



4. CCQE cross section model tuning

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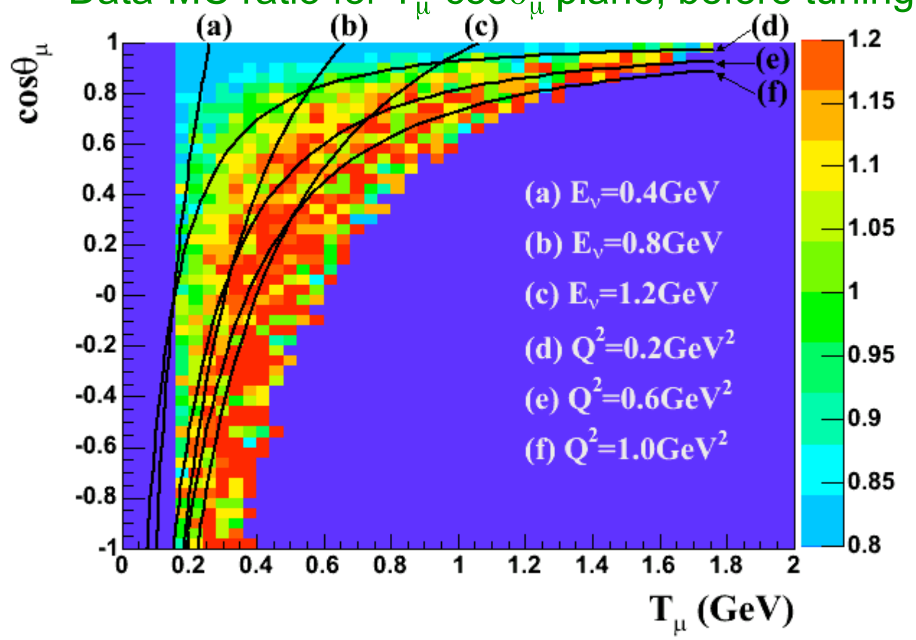
$$R(\text{interaction}[E_\nu, Q^2]) \propto \int (\text{flux}[E_\nu]) \times (\text{xs}[Q^2])$$

Data-MC mismatching follows Q^2 lines, not E_ν lines, therefore we can see the problem is not the flux prediction, but the cross section model

Data-MC ratio for T_μ-$\cos\theta_\mu$ plane, before tuning



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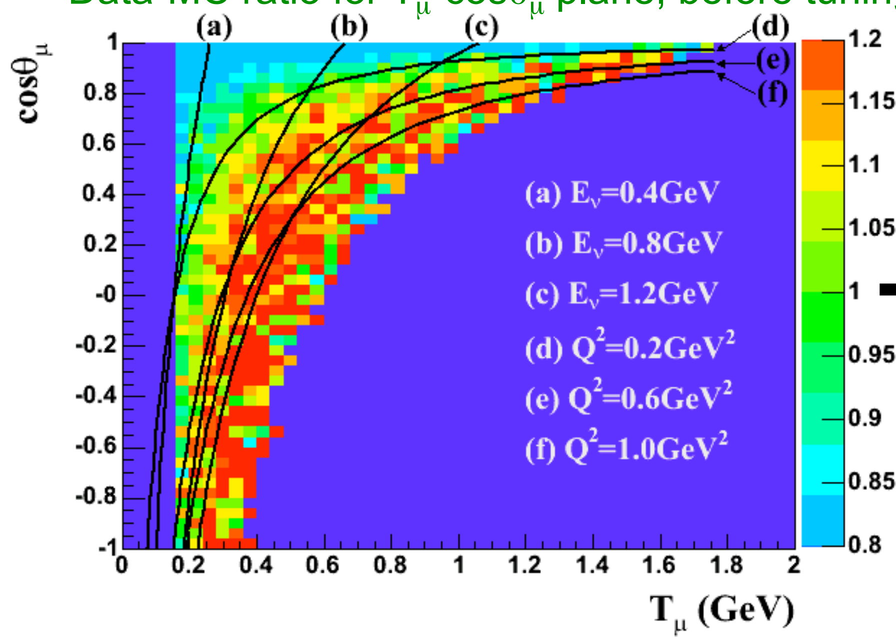
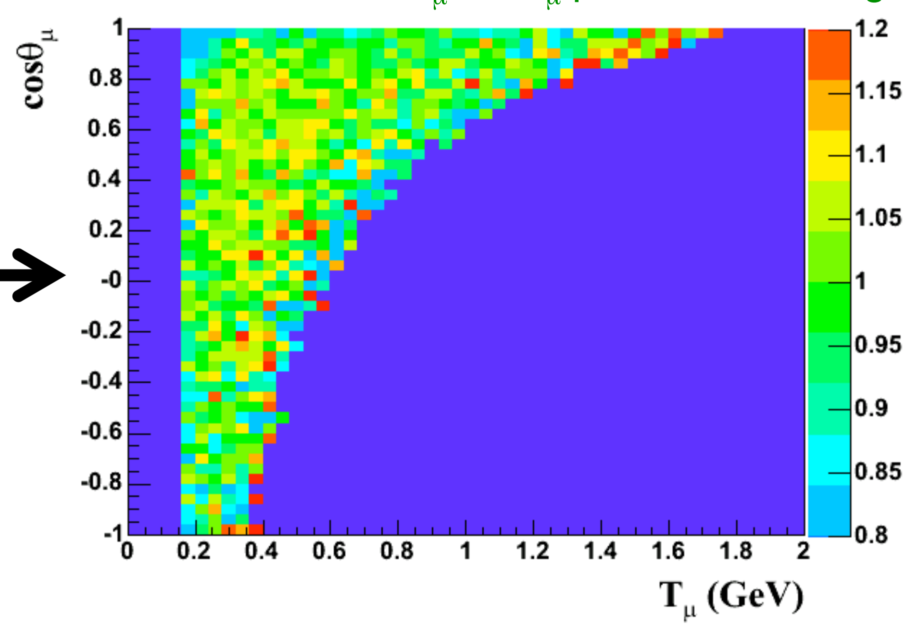
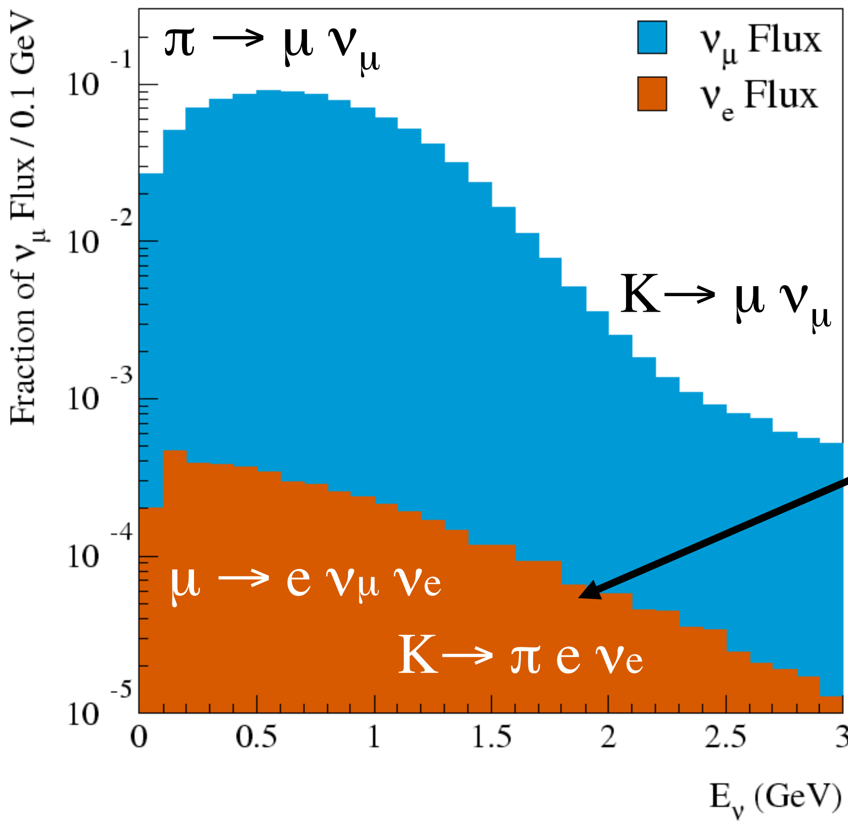


Data-MC ratio for T_μ-$\cos\theta_\mu$ plane,after tuning



4. ν_μCCQE for oscillation blind analysis



ν_e/ν_μ = 0.5%

Antineutrino content: 6%

"Intrinsic" $\nu_e + \bar{\nu}_e$ sources:

$\mu^+ \rightarrow e^+\, \bar{\nu}_\mu\, \nu_e$	(52%)
$K^+ \rightarrow \pi^0\, e^+\, \nu_e$	(29%)
$K^0 \rightarrow \pi\, e\, \nu_e$	(14%)
Other	(5%)

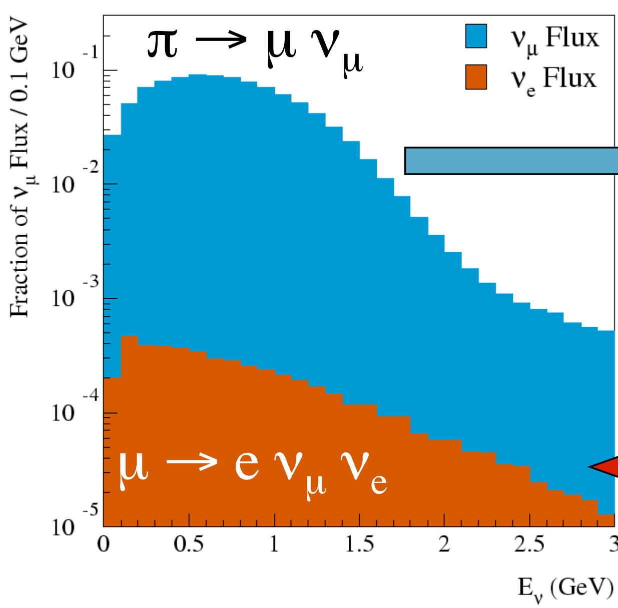
Since MiniBooNE is blind analysis experiment, we need to constraint intrinsic ν_e background without measuring directly

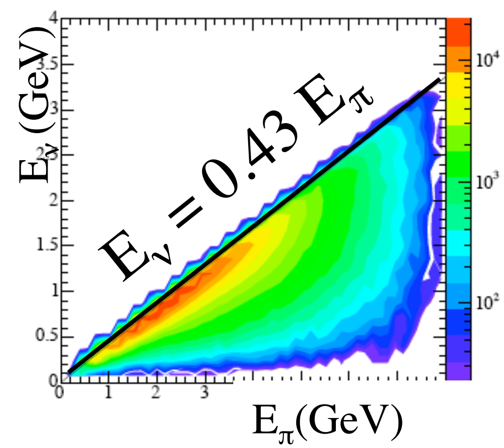
μ decay ν_e background is the biggest source of intrinsic ν_e, we wish to know their distribution without measuring them!

4. ν_μCCQE for oscillation blind analysis

measure ν_μ flux from ν_μCCQE event to constraint ν_e background from μ decay

ν_μCCQE is not "blinded" because we know no ν_e candidate is in data after ν_μCCQE cut. Kinematics allows connection to π flux, hence intrinsic ν_e background from μ decay is constraint. In the really, simultaneous fit of ν_eCCQE and ν_μCCQE take care of this.





4. MiniBooNE cross section results

NuInt09, May18-22, 2009, Sitges, Spain
All talks proceedings are available on online (open access),
http://proceedings.aip.org/proceedings/confproceed/1189.jsp

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In NuInt09, MiniBooNE had 6 talks and 2 posters

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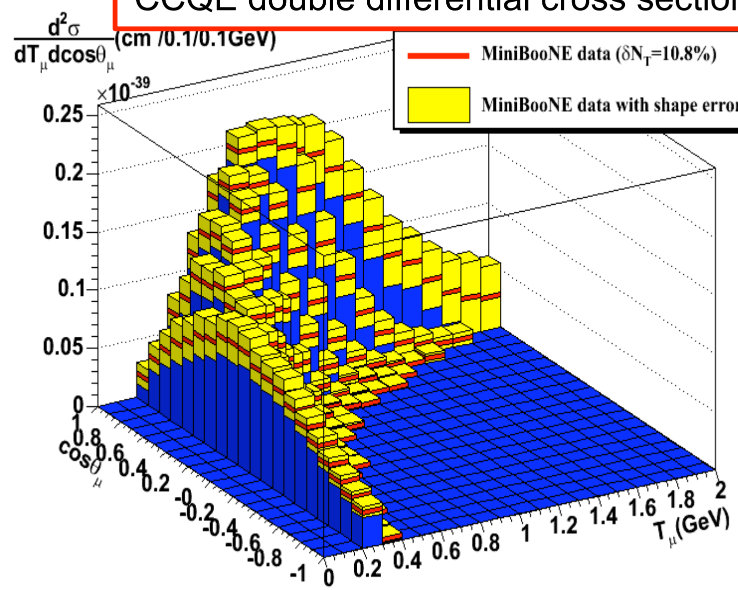
2. neutral current elastic (NCE) cross section measurement

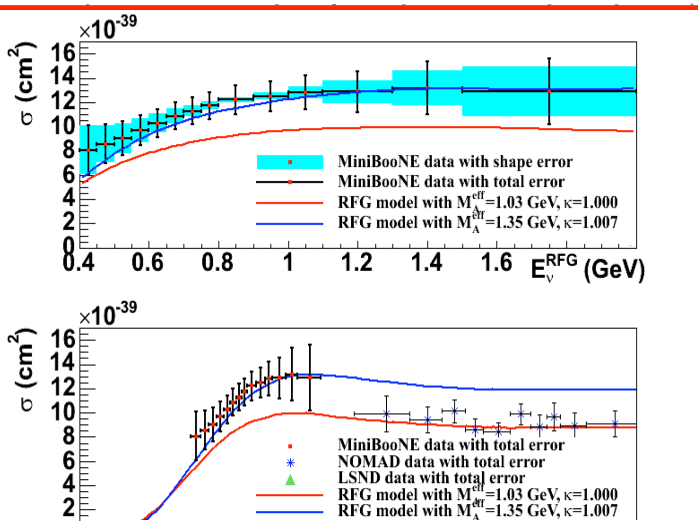
- first double differential cross section measurement
- observed large absolute cross section

by Colin Anderson, PRD81(2010)013005

4. ch … $CC\pi^+$) cross
   by
5. ch … π^o) cross s
   by
6. im … generator
   by
7. CC … ment
   by
8. an
   by

CCQE double differential cross section





Flux-unfolded total cross section

by Denis Perevalov

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- highest statistics cross section measurement
- new Δs (strange quark spin) extraction method

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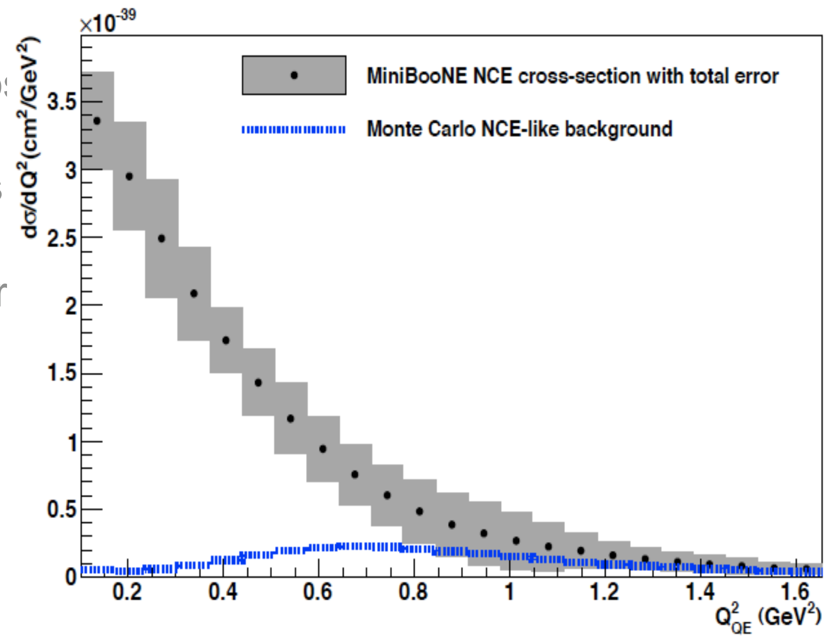
$$\nu_\mu + p \rightarrow \nu_\mu + p$$

$$\nu_\mu + n \rightarrow \nu_\mu + n$$

Flux-averaged NCE p+n differential cross section



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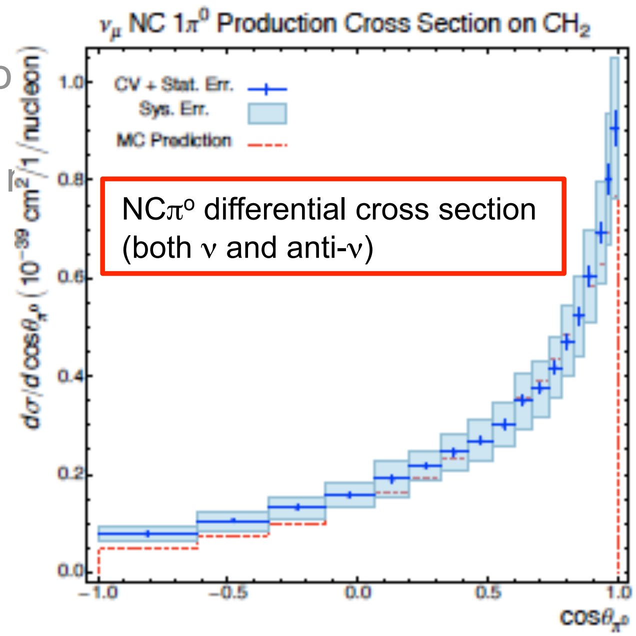

by Mike Wilking

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$$\nu_\mu + p(n) \rightarrow \mu + \Delta^{+(+)} \rightarrow \mu + p(n) + \pi^+$$
$$\nu_\mu + A \rightarrow \mu + A + \pi^+$$

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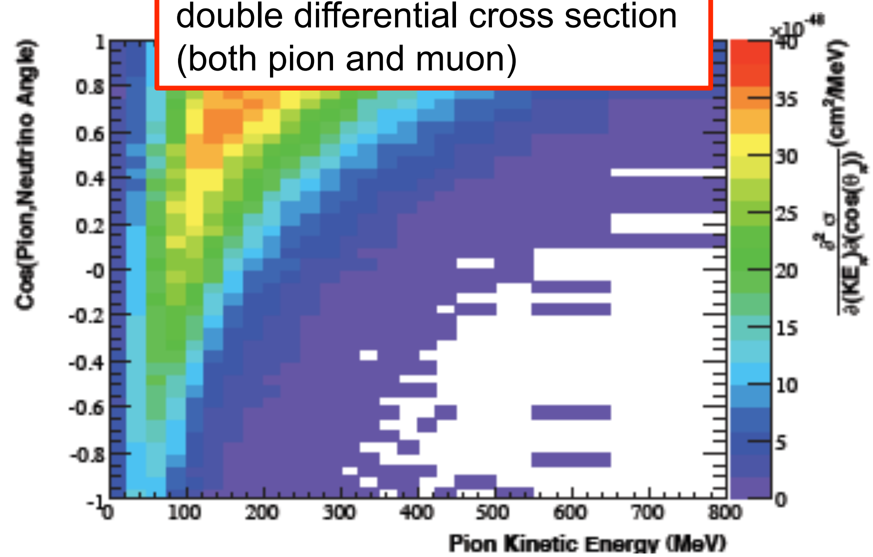
double differential cross section (both pion and muon)



by Bob Nelson

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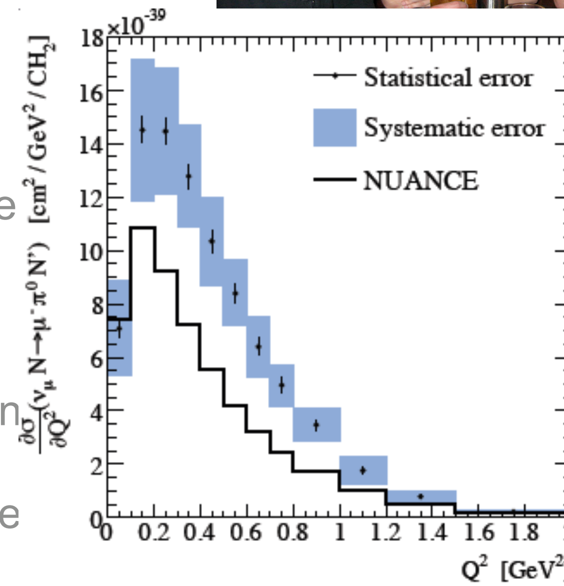

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- first differential cross section measurement
- observed large absolute cross section

CCπ^o Q^2 differential cross section

$$\nu_\mu + n \rightarrow \mu + \Delta^+ \rightarrow \mu + p + \pi^o$$

4. MiniBooNE cross section results

by Jarek Novak

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3. n… measurement (ν and anti-ν)
   by Colin Anderson, PRD81(2010)013005

- state-of-art models are implemented, tested

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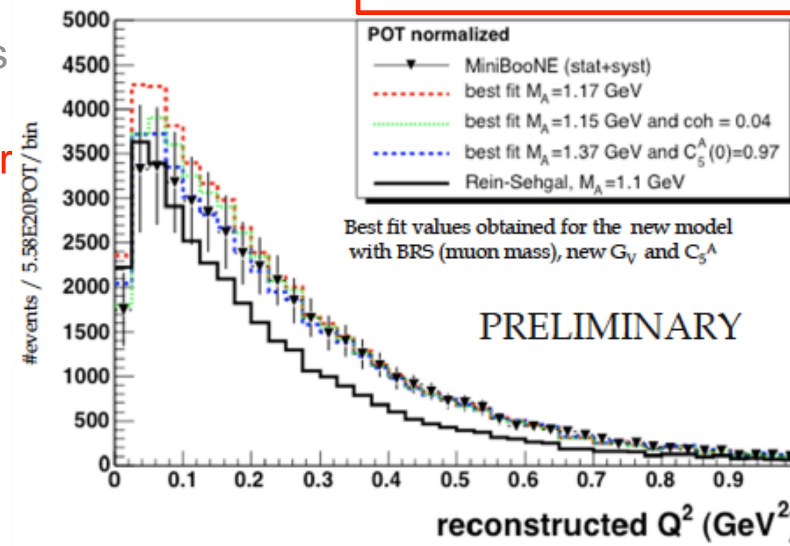
$M_A^{1\pi}$ fit with Q^2 distribution for various nuclear models



4. MiniBooNE cross section results

by Steve Linden

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3. neutral current π^o production (NCπ^o) cross section

- data is presented in theorist friendly style

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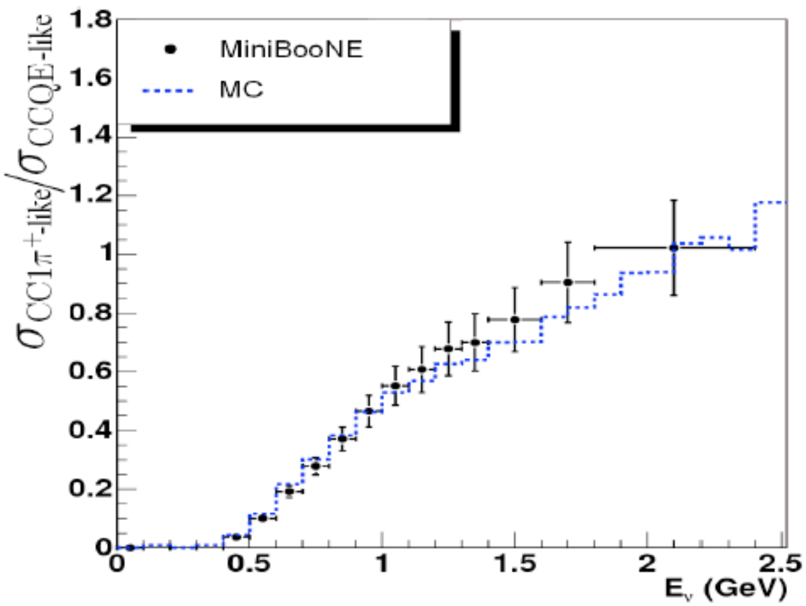

CCπ^+like/CCQElike cross section ratio by Joe Grange

4. MiniBooNE cross section results

NuInt09, May18-22, 2009, Sitges, Spain

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3. neutral current π^o production ($NC\pi^o$) cross section measuremen

4 ... secti

- highest statistics in this channel
- support neutrino mode result
- new method to measure neutrino contamination

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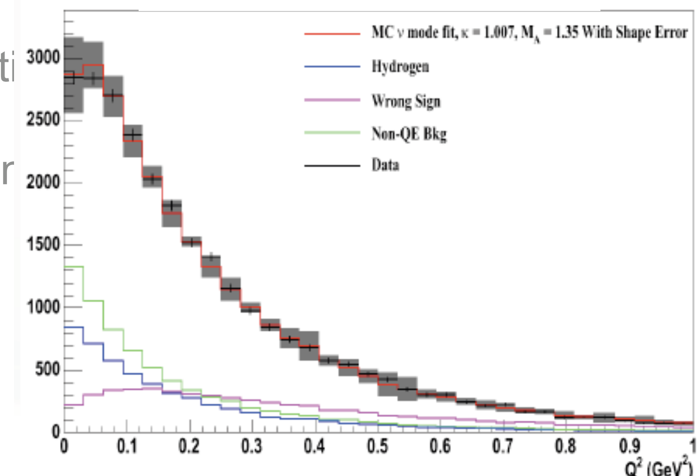
$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$

$$\left(\begin{array}{c} \bar{\nu}_\mu + {}^{12}C \rightarrow X + \mu^+ \\ \bar{\nu}_\mu + {}^{1}H \rightarrow n + \mu^+ \end{array} \right)$$



anti-νCCQE Q^2 distribution

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2. Neutrino beam

3. Events in the detector

4. Cross section model

5. Oscillation analysis and result

6. New Low energy excess result

7. Anti-neutrino oscillation result

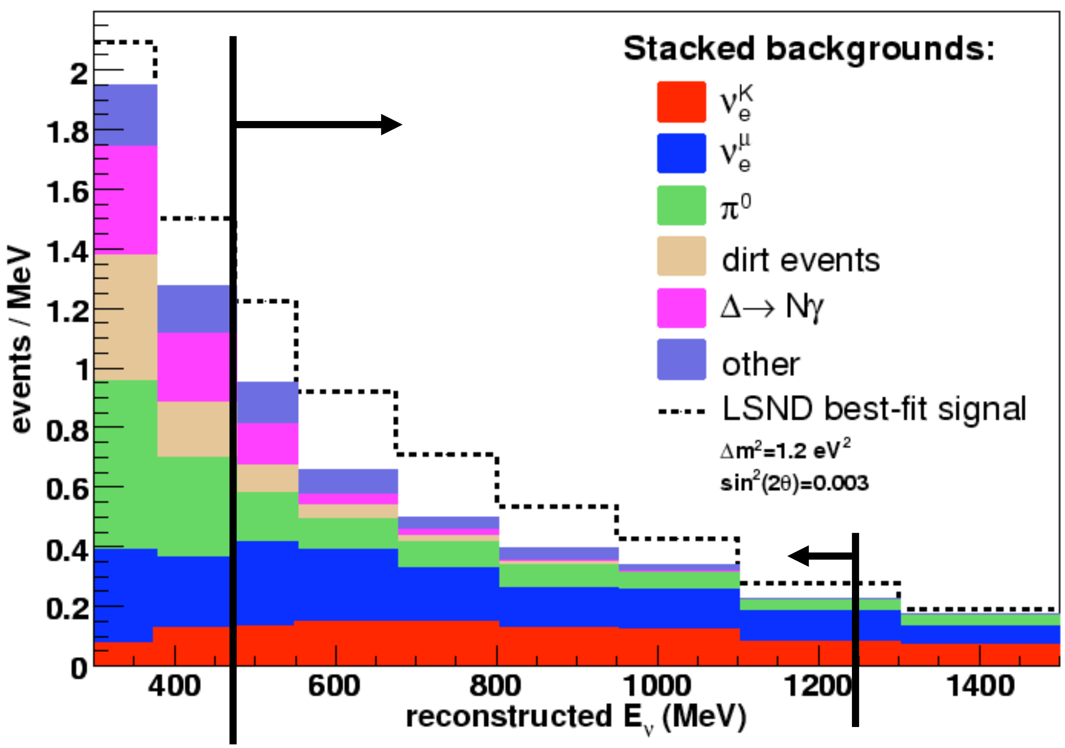
8. Neutrino disappearance result

9. Outlook

5. Oscillation analysis background summary

TBL analysis summary

- Oscillation analysis uses 475MeV<E<1250MeV



475 MeV – 1250 MeV

ν_e^K	94
ν_e^μ	132
π^0	62
dirt	17
$\Delta\rightarrow N\gamma$	20
other	33
total	358

LSND best-fit $\nu_\mu\rightarrow\nu_e$ 126

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TBL analysis summary

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475 MeV – 1250 MeV

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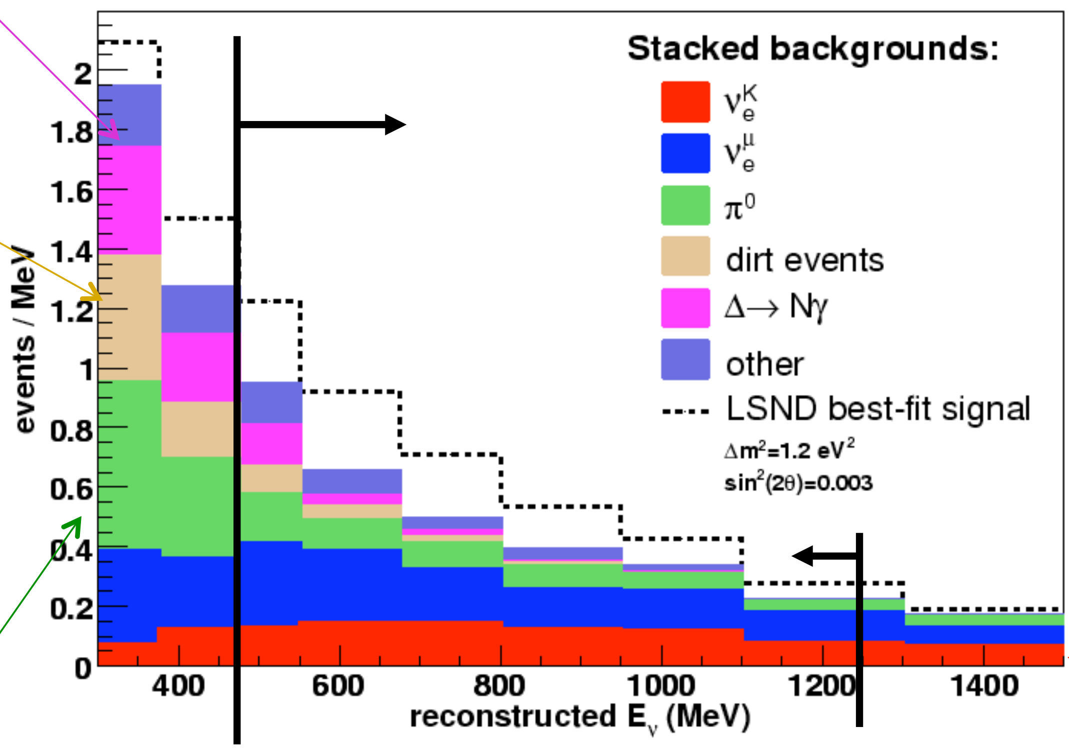
LSND best-fit $\nu_\mu \rightarrow \nu_e$ 126

Δ resonance rate is constrained from measured CCπ^o rate

dirt rate is measured from dirt data sample



ν_e from μ decay is constrained from ν_μCCQE measurement

ν_e from K decay is constrained from high energy ν_e event measurement

Asymmetric π^o decay is constrained from measured CCπ^o rate ($\pi^o \rightarrow \gamma$)

All backgrounds are measured in other data sample and their errors are constrained!

B.P.Roe,
Nucl.,Instrum.,Meth,A570(2007)157

5. Error analysis - Multisim

Input error matrix
keep all correlation
of systematics

"multisim"
nonlinear error propagation

Output error matrix
keep all correlation
of E_{ν}^{QE} bins

Multi-simulation (Multisim) method
many fake experiments (~1000) with different parameter set give the variation of correlated systematic errors for each independent error matrix

The total error matrix is the sum of all independent error matrix

The total error matrix is used for oscillation fit to extract the best fit Δm^2 and $\sin^2 2\theta$.

Input error matrices

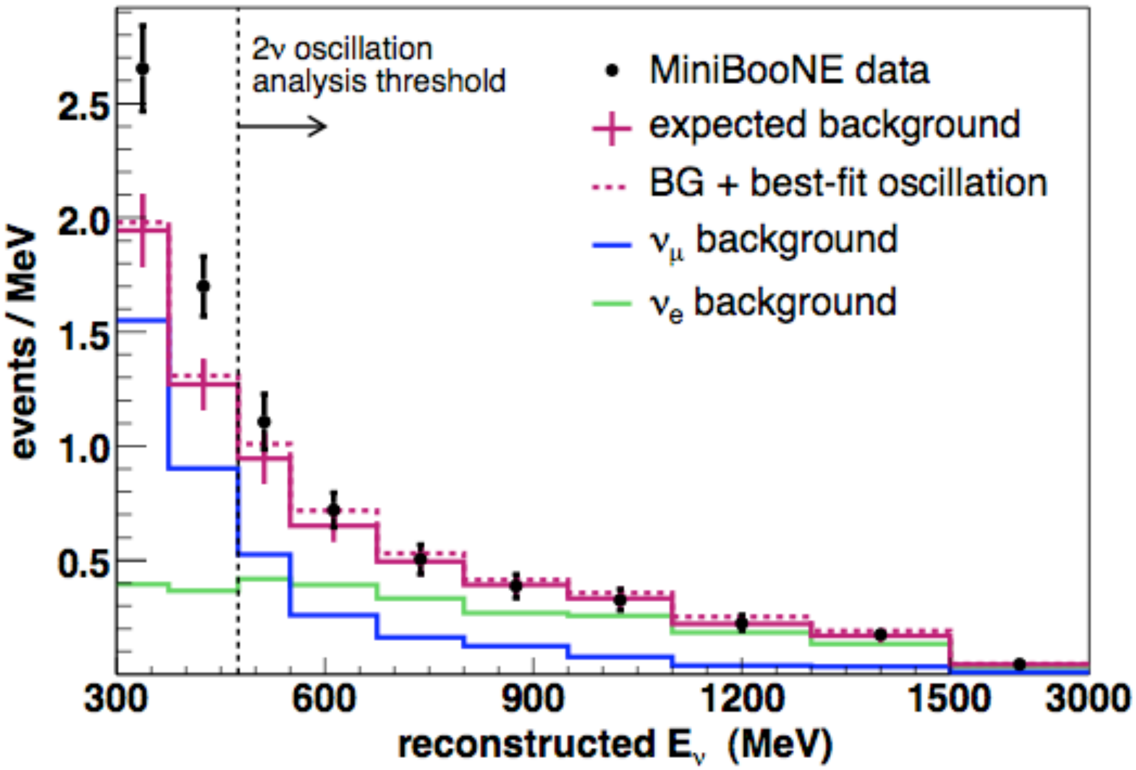
dependent

independent

π^+ production	(8 parameters)
π^- production	(8 parameters)
K^+ production	(7 parameters)
K^0 production	(9 parameters)
beam model	(8 parameters)
cross section	(27 parameters)
π^0 yield	(9 parameters)
dirt model	(1 parameters)
detector model	(39 parameters)

MiniBooNE collaboration,
PRL98(2007)231801

5. The MiniBooNE initial results



The best fit result shows no sign of an excess in the analysis region (where the LSND signal is expected from 1 sterile neutrino interpretation)

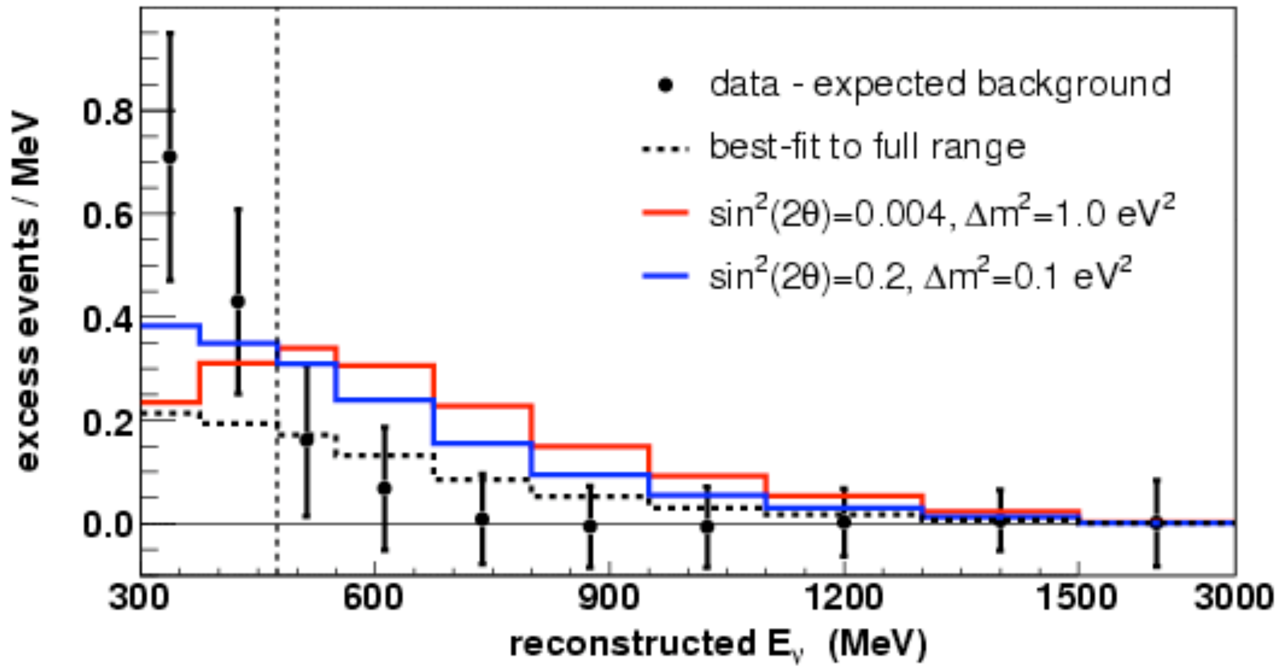
Visible excess at low E

MiniBooNE collaboration,
PRL98(2007)231801

5. Excess at low energy region?

There is statistically significant excess at low energy region.

The low energy excess is not consistent with any 2 neutrino massive oscillation models.



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6. Excess at low energy region?

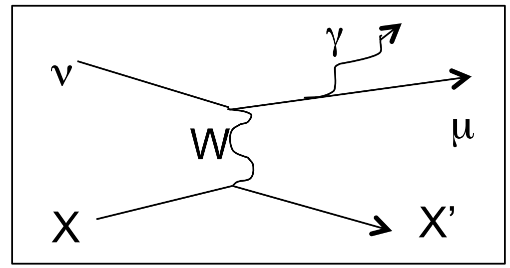
Commonplace idea Bodek, arXiv:0709.4004

Muon bremsstrahlung

$$\nu_\mu + X \rightarrow \cancel{\mu}^- + \gamma + X'$$

- We studied from our data, and rejected.

MiniBooNE collaboration, arXiv:0710.3897



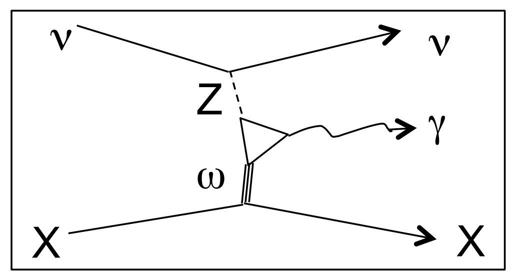
Harvey, Hill, Hill, PRL99(2007)261601

Standard model, but new

Anomaly mediated gamma emission

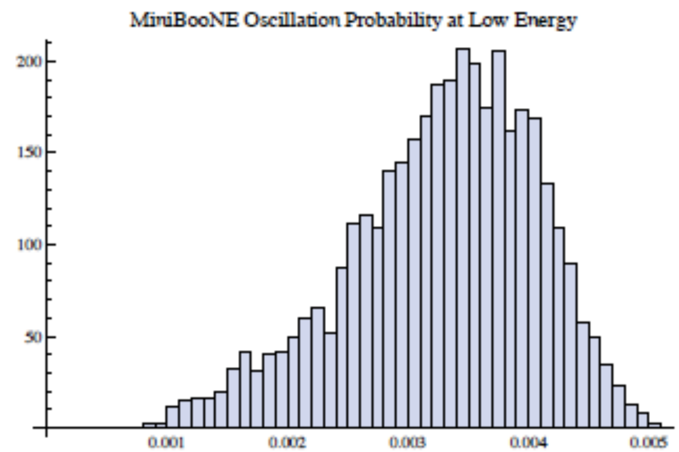
$$\nu_\mu + X \rightarrow \nu_\mu + X + \gamma$$

- Under study, need to know the coupling constant
- naïve approximation, same cross section for ν-N and $\bar{\nu}$-N



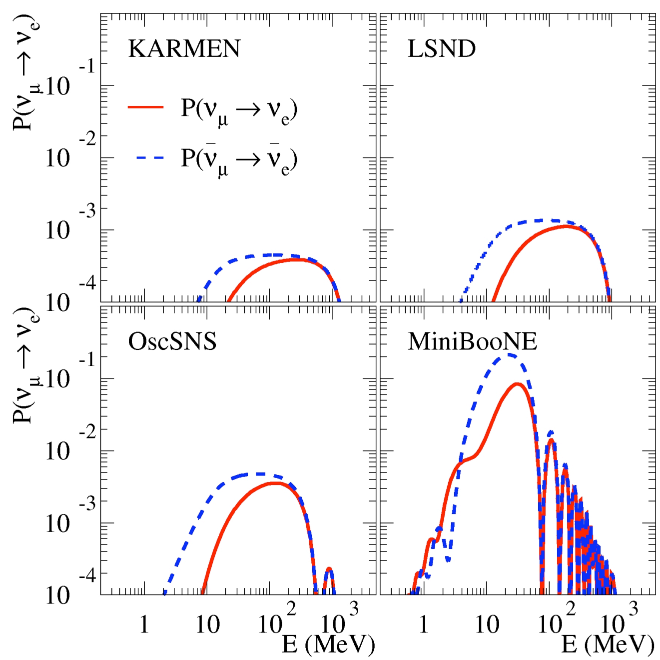
6. Excess at low energy region?

Nelson, Walsh,
PRD77(2008)033001



Beyond the Standard model (most popular)

New gauge boson production in the beamline
- can accommodate LSND and MiniBooNE
- solid prediction for anti-neutrinos.



Lorentz violating oscillation model
- can accommodate LSND and MiniBooNE
- predict low energy excess before MiniBooNE result.
- Under study

Kostelecky, TK, Tayloe,
PRD74(2006)105009

6. Oscillation analysis update

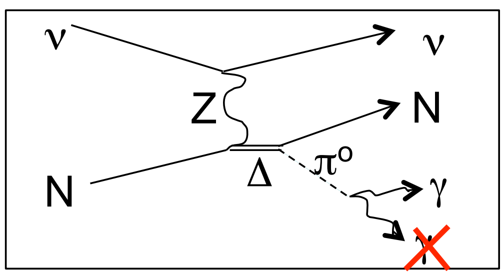
We re-visit all background source, to find any missing components

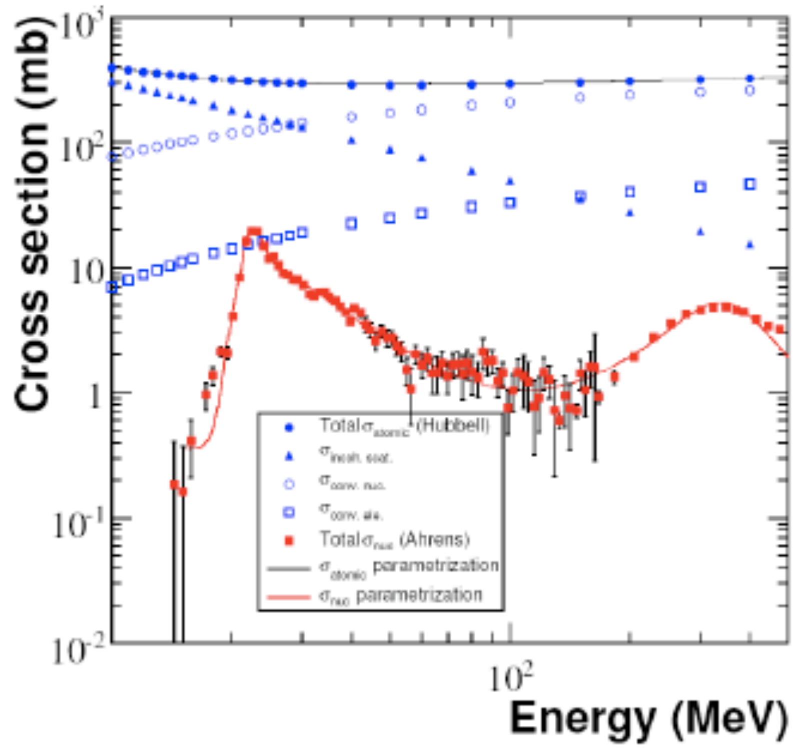
Photonuclear effect

Low energy gamma can excite nuclei, an additional source to remove one of gamma ray from NCπ^o

Photonuclear effect

$$\pi^o \rightarrow \gamma\gamma \xrightarrow{\text{photonuclear}} \gamma$$





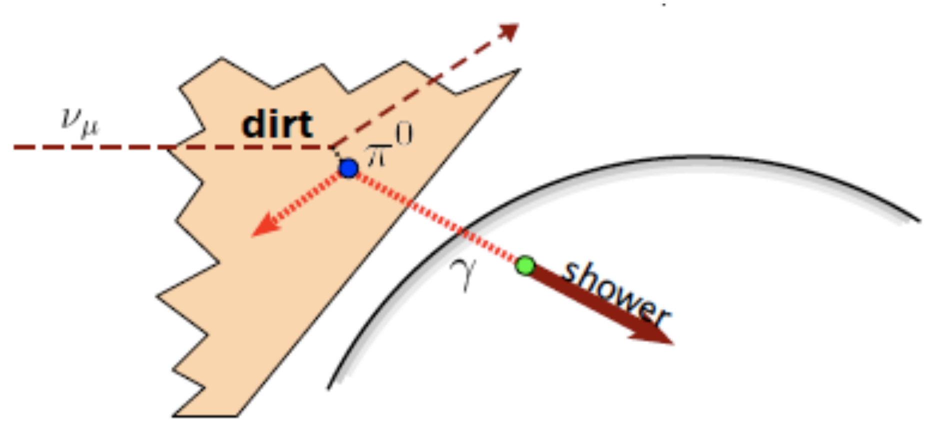
Other missing processes, (π-C elastic scattering, radiative π^- capture, π induced Δ radiative decay) are negligible contribution to the background

6. Oscillation analysis update

We re-visit all background source, to find any missing components

New dirt background cut

- "dirt event" is the interaction happens outside of the detector
- mostly po made outside of the detector
- new cut remove 85% of dirt originated backgrounds



6. Oscillation analysis update

We re-visit all background source, to find any missing components

New flux prediction error
 - external measurement error directly propagates to MiniBooNE analysis, without relying on the fitting.

New radiative gamma error
- new analysis take account the re-excitation of Delta from struck pion, this increases the error from 9% to 12%.

New low energy bin
 - analysis is extended down to 200MeV

New data set
 - additional 0.83E20 POT data.

MiniBooNE collaboration,
PRL102(2009)101802

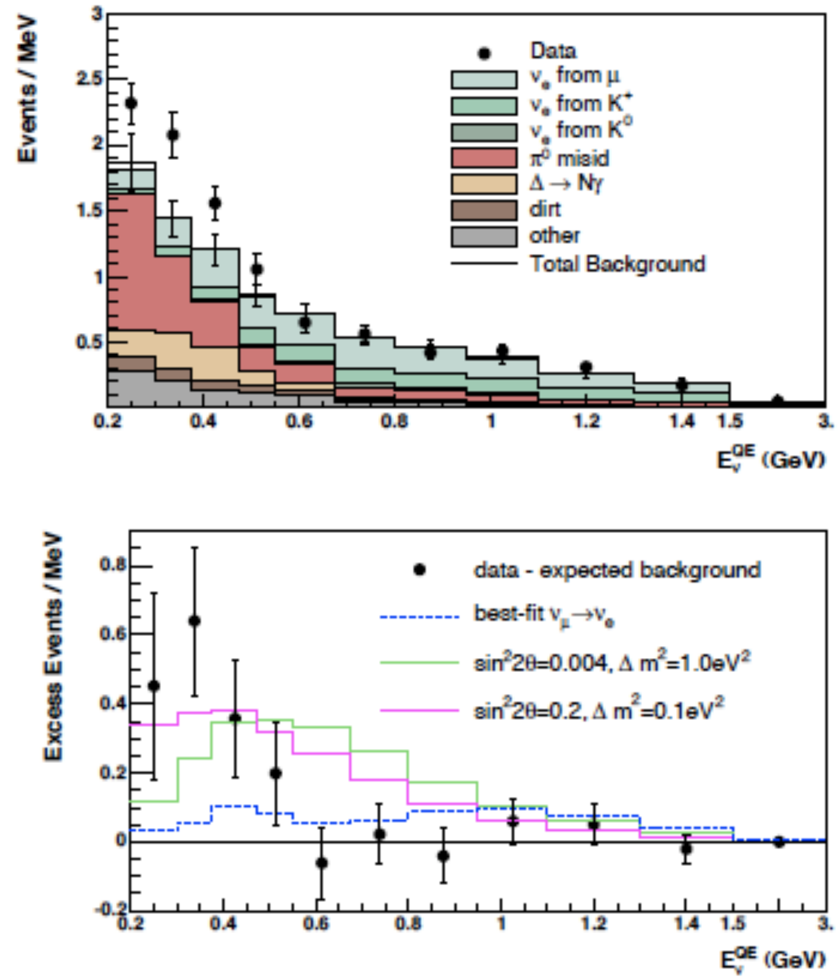
6. New oscillation analysis result

New ν_e appearance oscillation result

- low energy excess stays, the original excess in 300-475MeV becomes 3.4σ from 3.7σ after 1 year reanalysis.

- again, the shape is not described by any of two neutrino massive oscillation models

Now, we are ready to test exotic models, through antineutrino oscillation data



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6. New Low energy excess result

7. Anti-neutrino oscillation result

8. Neutrino disappearance result

9. Outlook

MiniBooNE collaboration,
PRL103(2009)111801

7. Antineutrino oscillation result

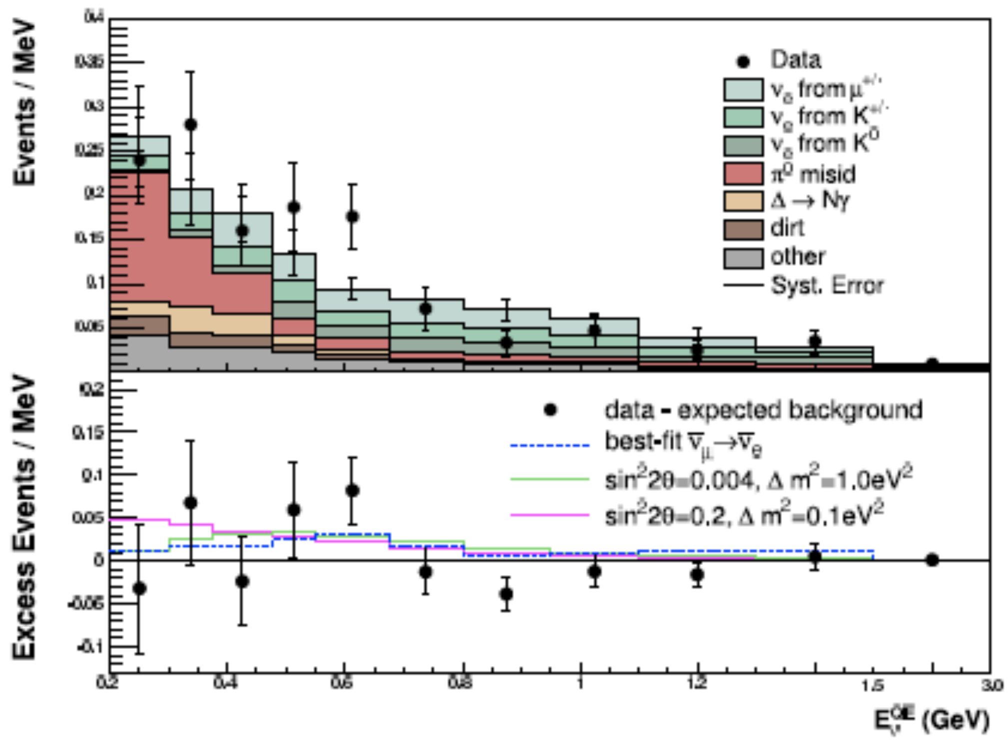
Many exotic models have some kind of predictions in antineutrino mode.

Analysis is quite parallel, because MiniBooNE doesn't distinguish e^- and e^+ or μ^- and μ^+ on event-by-event basis.

$$\nu_e + n \rightarrow p + e^-$$

$$\bar{\nu}_e + p \rightarrow n + e^+$$

Bottom line, we don't see the low energy excess.



MiniBooNE collaboration,
PRL103(2009)111801

7. Antineutrino oscillation result

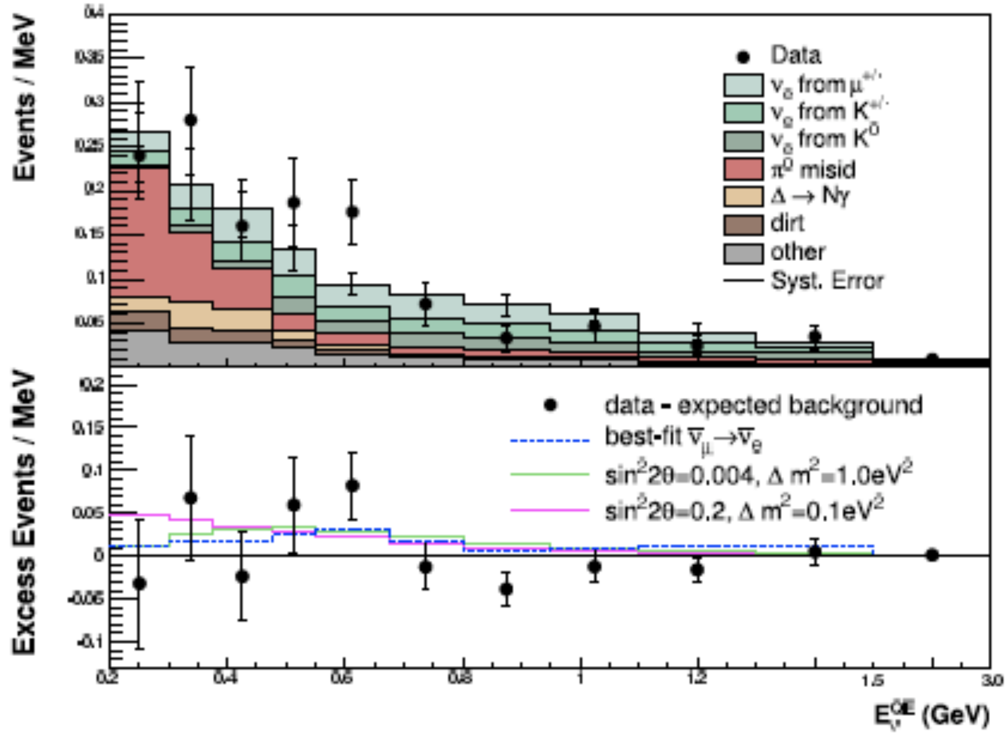
Implications

So many to say about models to explain low energy excess…

- The models based on same NC cross section for ν and anti-ν (e.g., anomaly gamma production) are disfavored.

-The models proportioned to POT (e.g., physics related to the neutral particles in the beamline) are disfavored.

- The models which predict all excess only in neutrino mode, but not antineutrino are favored, such as neutrino-only induced excess



Hi theorists! new models are welcome!

MiniBooNE collaboration,
arXiv:1007.1150

7. New antineutrino oscillation result

- Antineutrino mode is the direct test of LSND signal
- Analysis is limited with statistics

New antineutrino oscillation result

	200-475 MeV	475-1250 MeV	200-3000 MeV
anti ν_e candidate	119	120	277

- 70% more data
- low level checks have been done (beam stability, energy scale)
- new dirt event rate measurement (consistent with neutrino mode)
- new NCπ^o rate measurement (consistent with neutrino mode)
- ν fraction is measured in anti-ν beam

New antineutrino oscillation result
(presented at Neutrino 2010, Athens)

MiniBooNE collaboration,
arXiv:1007.1150

7. New antineutrino oscillation result

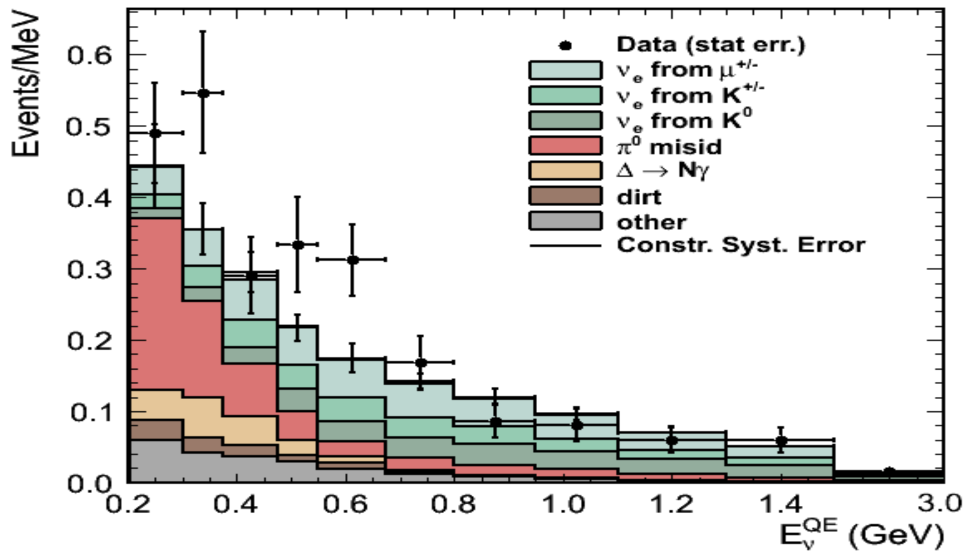
- Antineutrino mode is the direct test of LSND signal
- Analysis is limited with statistics

	200-475 MeV	475-1250 MeV	200-3000 MeV
anti ν_e candidate	119	120	277
MC (stat+sys)	100.5 ± 14.3	99.1 ± 13.9	233.8 ± 22.5
Excess (stat+sys)	18.5 ± 14.3 (1.3σ)	20.9 ± 13.9 (1.5σ)	43.2 ± 22.5 (1.9σ)

New antineutrino oscillation result

- 70% more data
- low level checks have been done (beam stability, energy scale)
- new dirt event rate measurement (consistent with neutrino mode)
- new NCπ^o rate measurement (consistent with neutrino mode)
- ν fraction is measured in anti-ν beam

MiniBooNE now see the excess in LSND-like Δm^2 region!



MiniBooNE collaboration,
arXiv:1007.1150

7. New antineutrino oscillation result

- Antineutrino mode is the direct test of LSND signal
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	before fit	
	χ^2/NDF	probability
$475 < E_\nu^{QE} < 1250$ MeV	18.5/6	0.5%

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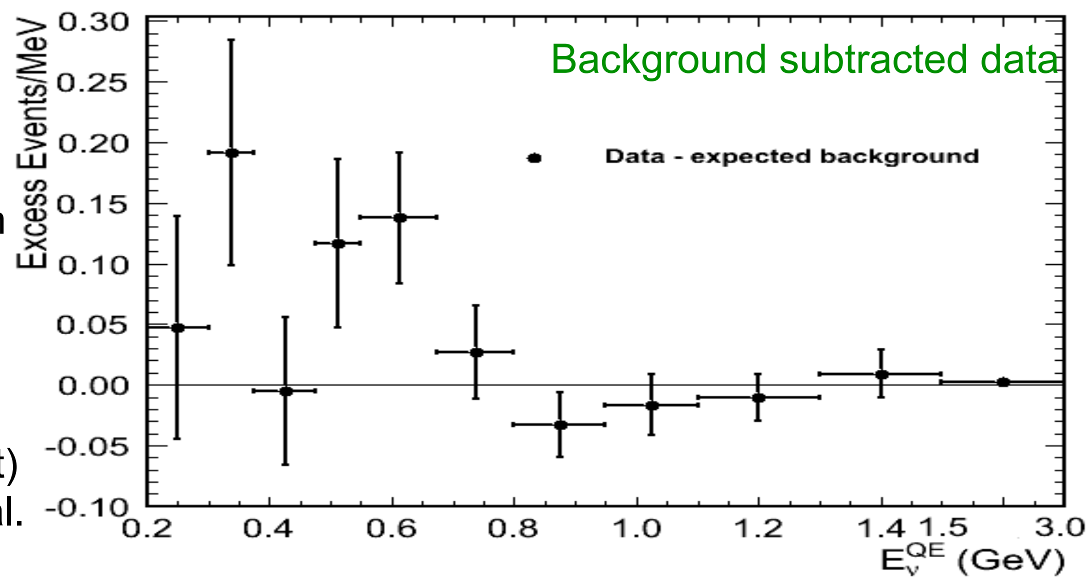
- flatness test (model independent test) shows statistically significance of signal.



MiniBooNE collaboration,
arXiv:1007.1150

7. New antineutrino oscillation result

- Antineutrino mode is the direct test of LSND signal
- Analysis is limited with statistics

	before fit		after fit	
	χ^2/NDF	probability	χ^2/NDF	probability
$475 < E_\nu^{QE} < 1250$ MeV	18.5/6	0.5%	8.0/4	8.7%

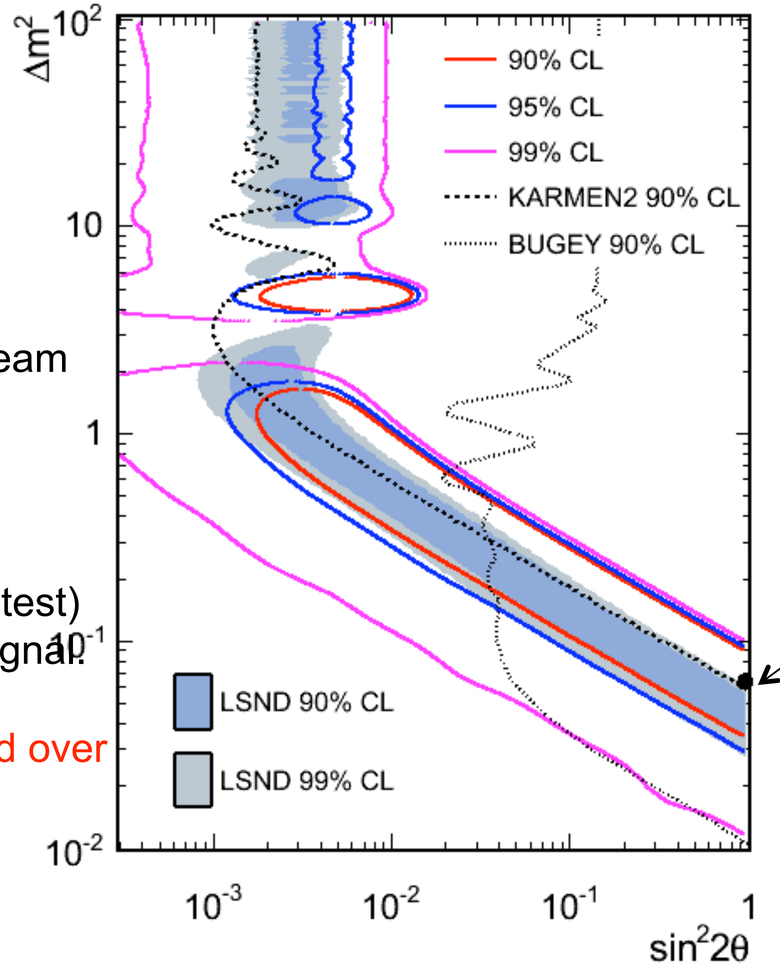
New antineutrino oscillation result

- 70% more data
- low level checks have been done (beam stability, energy scale)
- new dirt event rate measurement (consistent with neutrino mode)
- new NCπ^o rate measurement (consistent with neutrino mode)
- ν fraction is measured in anti-ν beam

MiniBooNE now see the excess in LSND-like Δm^2 region!

- flatness test (model independent test) shows statistically significance of signal.

2 massive neutrino model is favored over 99.4% than null hypothesis



E>475 MeV

Best ft point
$\Delta m^2 = 0.064 eV^2$
$\sin^2 2\theta = 0.96$

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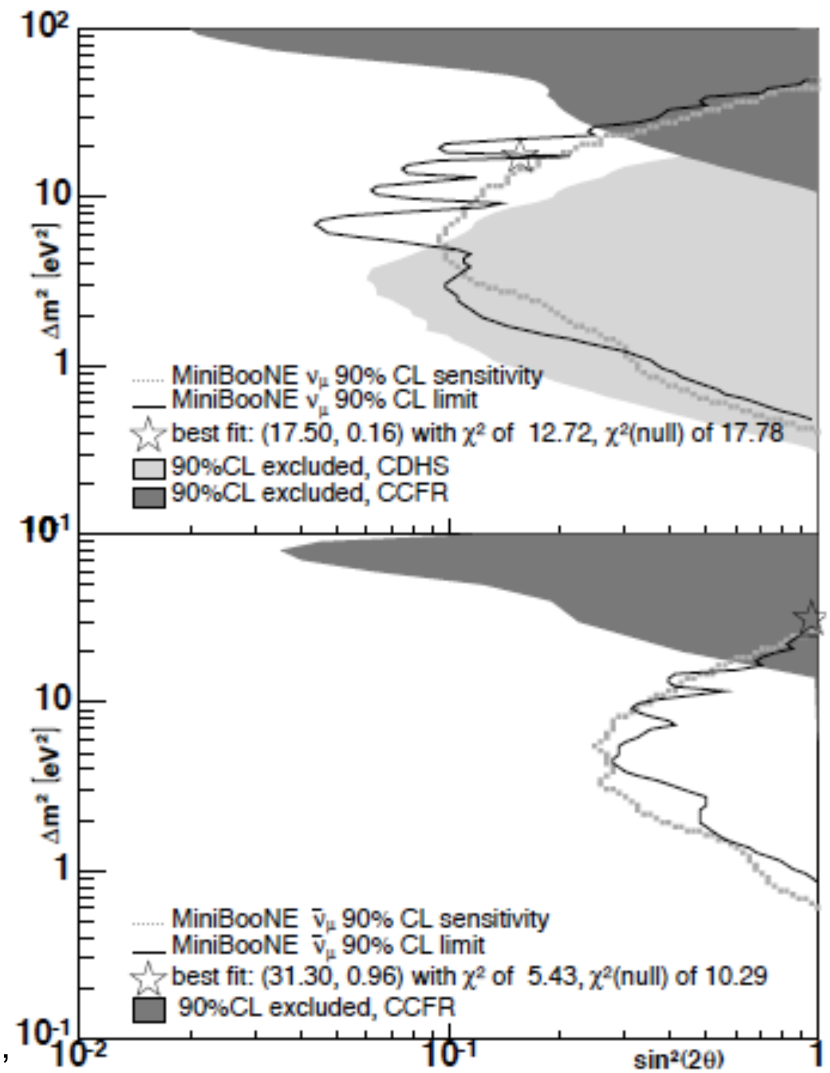
MiniBooNE collaboration,
PRL103(2009)061802

8. Neutrino disappearance oscillation result

ν_μ and anti-ν_μ disappearance oscillation

- test is done by shape-only fit for data and MC with massive neutrino oscillation model.

- MiniBooNE can test unexplored region by past experiments, especially there is no tests for antineutrino disappearance between Δm^2=10eV^2 and atmospheric Δm^2 .

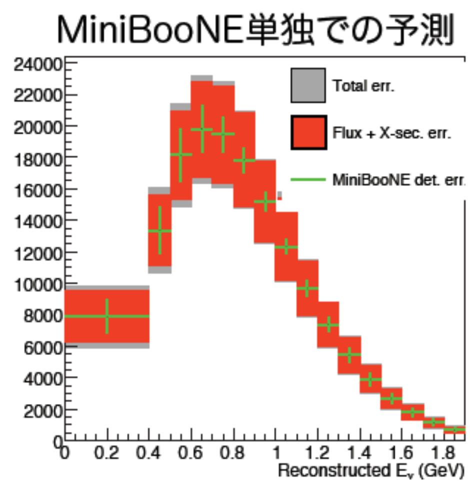


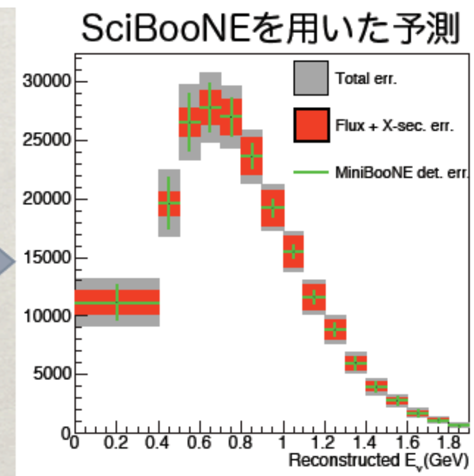
8. Neutrino disappearance oscillation result

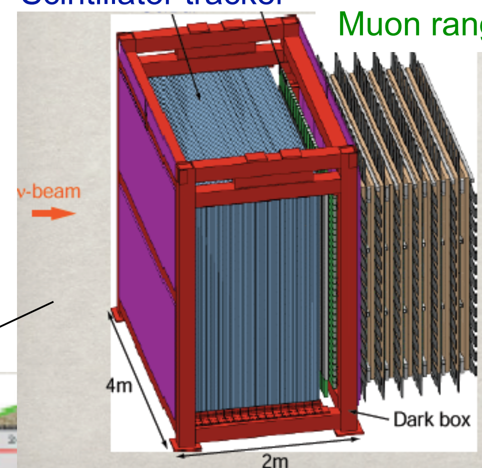
MiniBooNE-SciBooNE combined ν_μ disappearance oscillation analysis

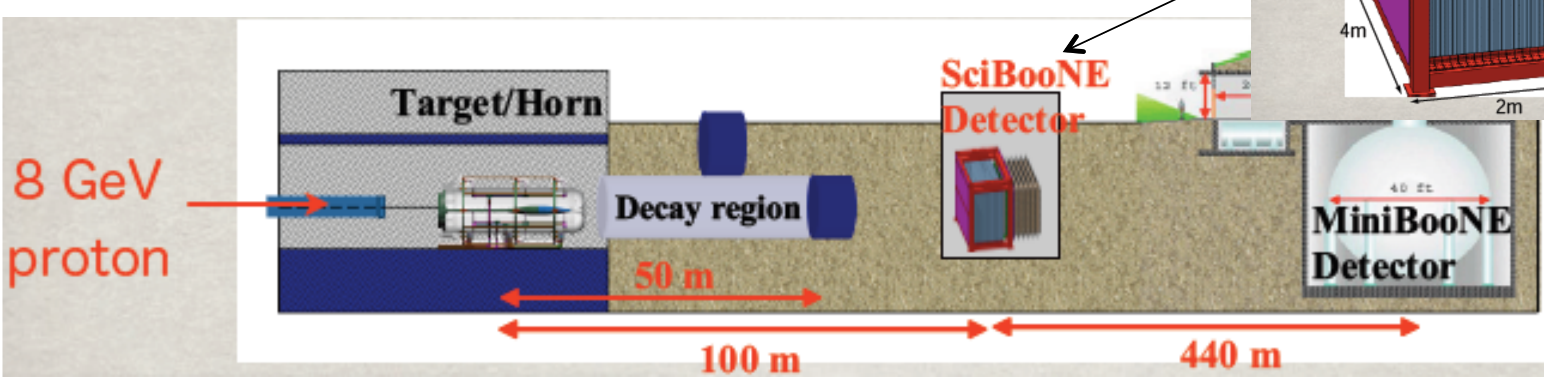
- combined analysis with SciBooNE can constrain Flux+Xsec error.

Flux-> same beam line
Xsec->same target (carbon)







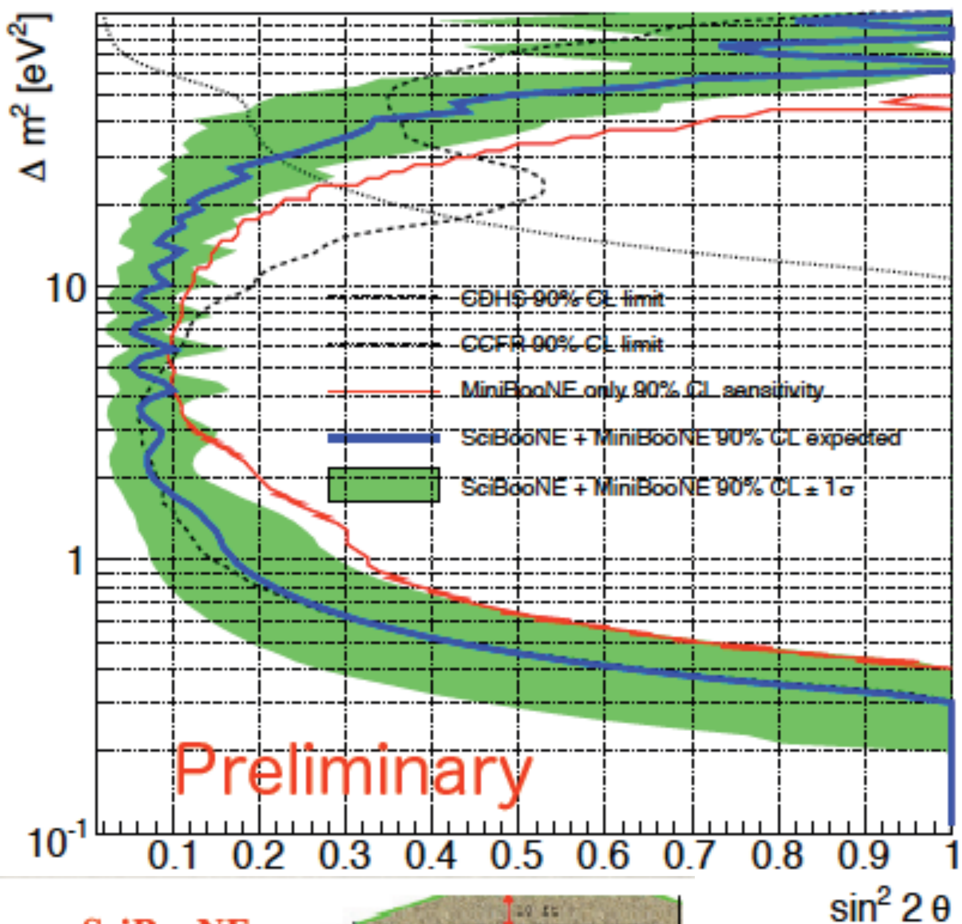


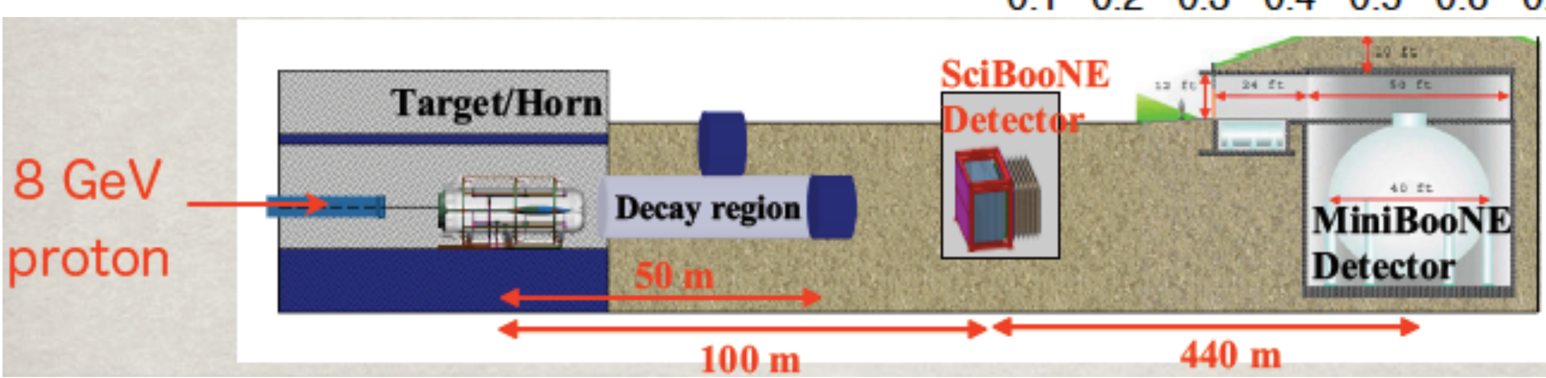
8. Neutrino disappearance oscillation result

MiniBooNE-SciBooNE combined ν_μ disappearance oscillation analysis

- combined analysis with SciBooNE can constrain Flux+Xsec error.
Flux-> same beam line
Xsec->same target (carbon)

- this significantly improves sensitivities, especially at low Δm^2. An analysis for anti-ν_μ is ongoing.





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9. **Outlook**

9. MiniBooNE oscillation result summary

Neutrino mode analysis
- no excess is observed in the energy region where excess is expected from LSND
- significant excess is observed in low energy region

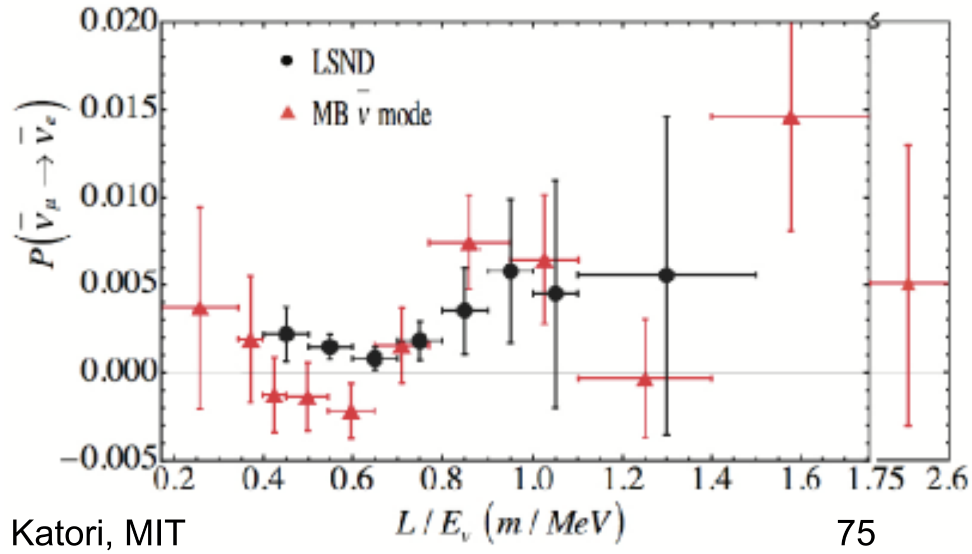
Antineutrino mode analysis
- small excess is observed in low energy region
- LSND consistent excess is observed in the oscillation energy region

These results are not main interest of Neutrino community (this is not θ_{13} nor leptonic CP violation nor Majorana mass measurement).

There is no convincing theoretical model to solve all mysteries.

Is MiniBooNE wrong?

MiniBooNE-LSND comparison in L/E



MiniBooNE collaboration,
PRD81(2010)092005

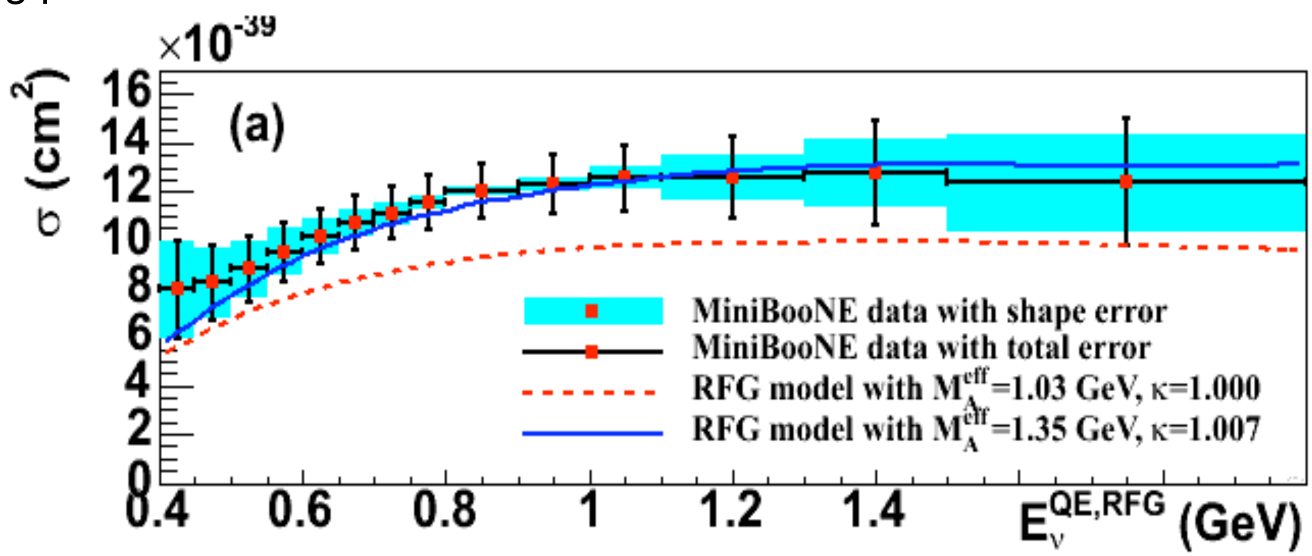
9. MiniBooNE CCQE absolute cross section

CCQE total cross section from MiniBooNE

MiniBooNE observed 30% higher neutrino cross section from RFG model with world averaged nuclear parameter from all past precise bubble chamber experiments.

When we first published this, we got so many criticism. Even a theorist claimed "MiniBooNE overestimate cross section!"

…but there is a turning point…



9. MiniBooNE CCQE absolute cross section

Martini et al

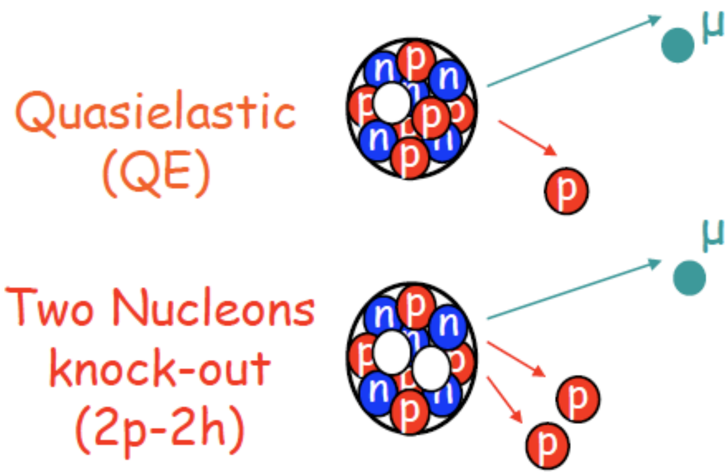
CCQE total cross section from MiniBooNE and RPA model

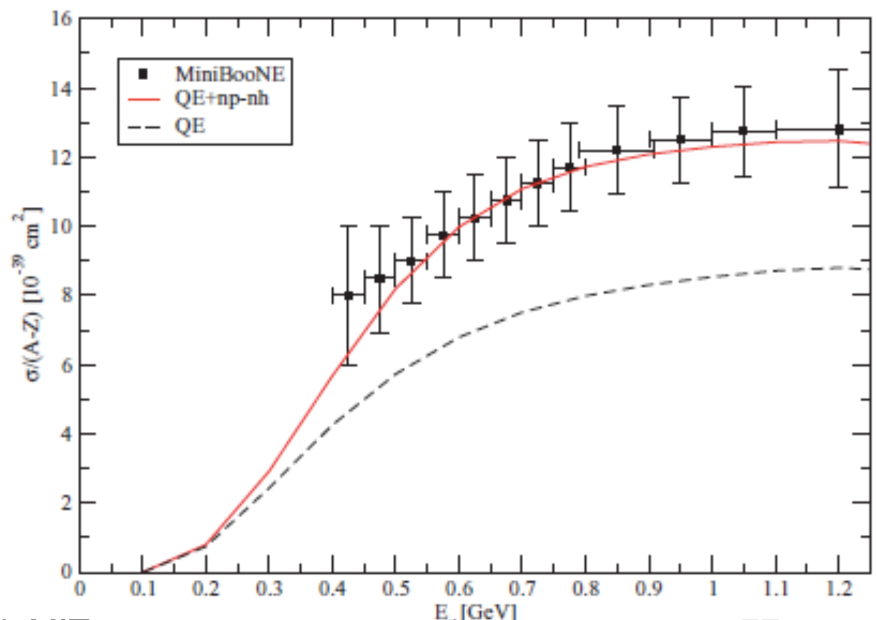
Martini et al.,
PRC80(2009)065501

Martini et al published their new RPA calculation result. They took into account the detail of nucleon emission channel (np-nh effect) and they explained MiniBooNE data.

Suddenly, many theorists start to appreciate this discovery by MiniBooNE.

So why all past experiments couldn't find this?





Martini et al

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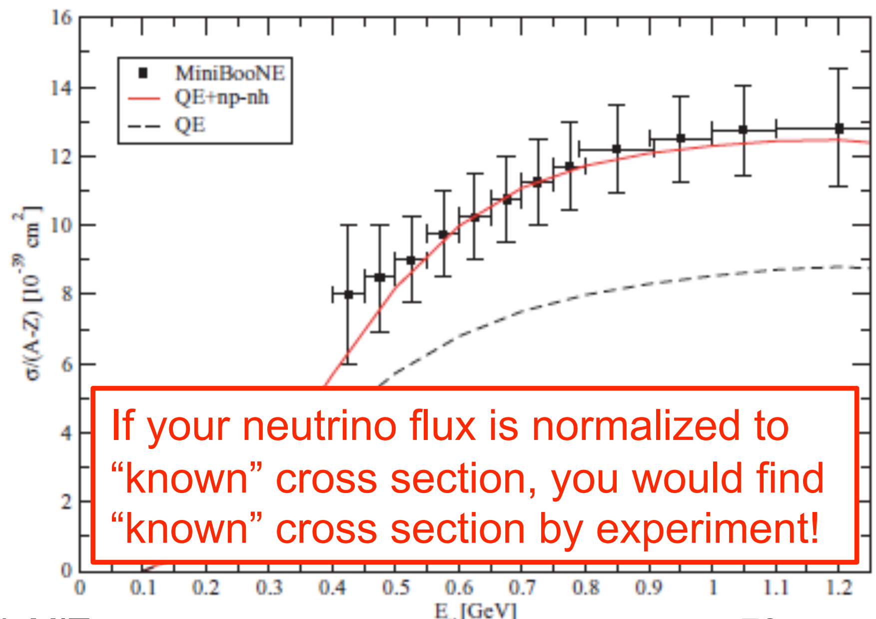
So why all past experiments couldn't find this?

There is a tendency for people to measure and discover what is predicted

Phys. Rev. DXX, (19XX)

The distribution of events in neutrino energy for the 3C $\nu d \to \mu^- p p_s$ events is shown in Fig. 4 together with the quasielastic cross section $\sigma(\nu n \to \mu^- p)$ calculated using the standard $V-A$ theory with $M_A = 1.05 \pm 0.05$ GeV and $M_V = 0.84$ GeV. The absolute cross sections for the CC interactions have been measured using the quasielastic events and its known cross section.[4]



9. MiniBooNE CCQE absolute cross section

We shouldn’t do this kind of mistake.

Many of MiniBooNE result are unexpected, and unexplained. But that cannot be a reason to be wrong. Remember, how much our naïve assumptions were correct for what we call now standard neutrino model.

(Neutrino 2006, Murayama)
Solar neutrino oscillation solution is SMA, because it’s pretty
-> Wrong, LMA is the right solution

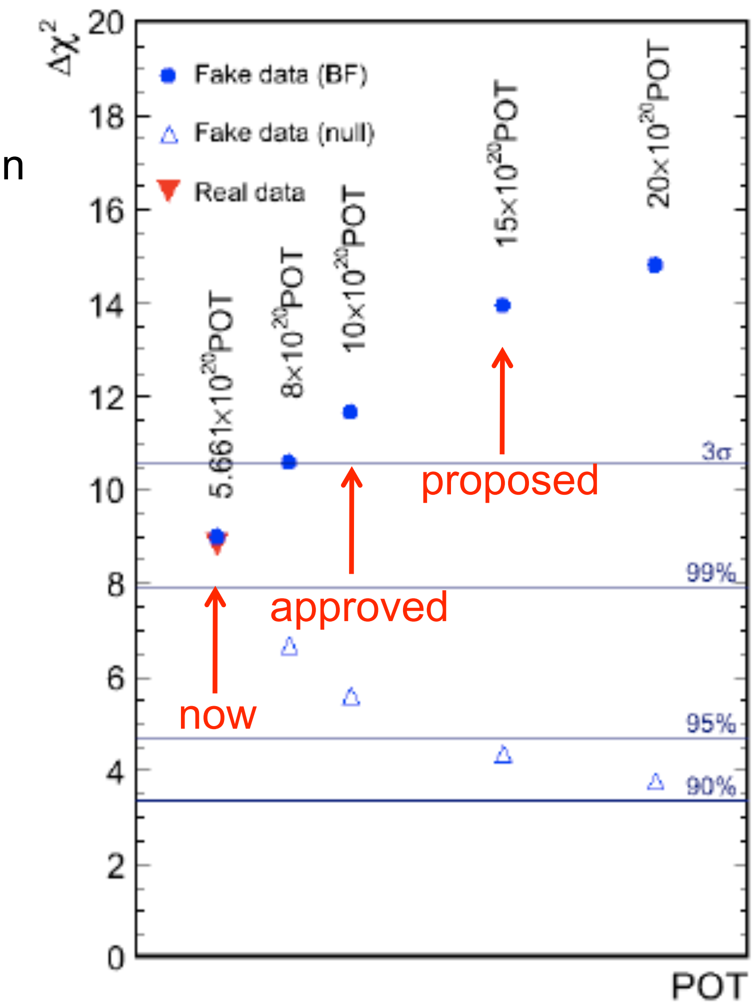
Natural scale of neutrino mass is ~10-100eV^2 because it’s cosmologically interesting
-> Wrong, much smaller

Atmospheric mixing should be small like CKM matrix element V_{cb}~0.04, cannot be large
-> Wrong, much larger

Neutrino physics keep surprising us, so does MiniBooNE!

9. MiniBooNE future plan

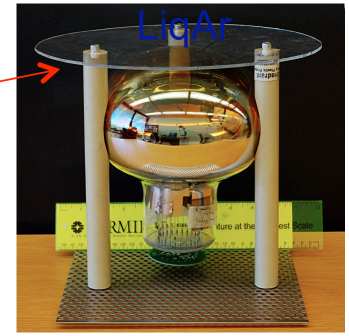
We continue to take data until March 2012 (approved), then we will double the statistics and expect 3σ excess in antineutrino mode. We are putting a proposal for 15E20 extension.

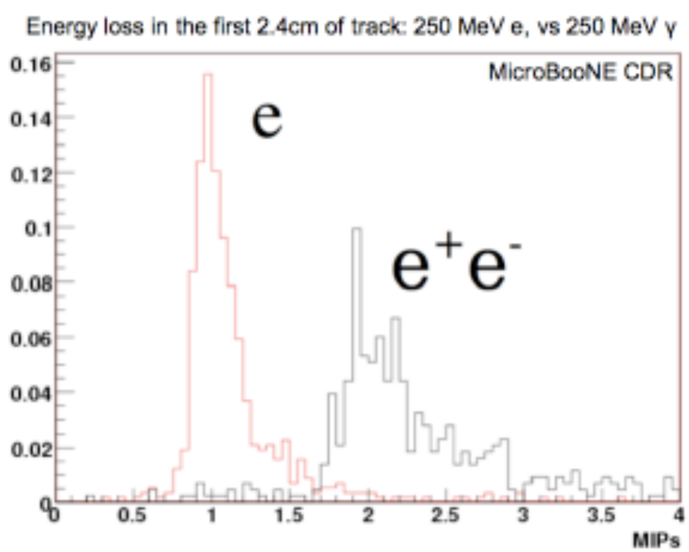


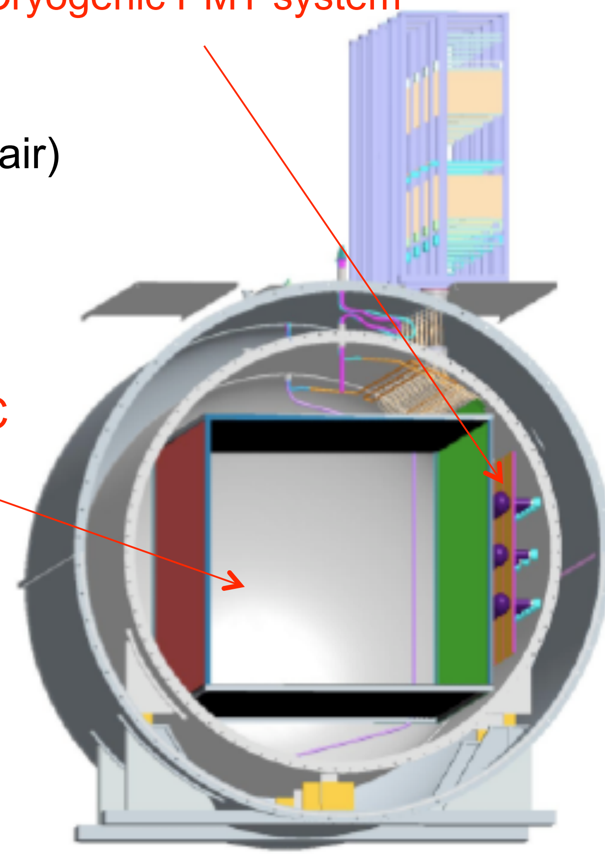
9. MicroBooNE

Liquid Argon TPC experiment at Fermilab

- 70 ton fiducial volume LiqAr TPC
- R&D detector for future large LiqAr TPC for DUSEL
- 3D tracker (modern bubble chamber)
- data taking will start from 2013(?)
- dE/dx can separate single electron from gamma ray (e^+e^- pair)







BooNE collaboration

University of Alabama
Bucknell University
University of Cincinnati
University of Colorado
Columbia University
Embry Riddle Aeronautical University
Fermi National Accelerator Laboratory
Indiana University
University of Florida
Los Alamos National Laboratory
Louisiana State University
Massachusetts Institute of Technology
University of Michigan
Princeton University
Saint Mary's University of Minnesota
Virginia Polytechnic Institute
Yale University

Thank you for your attention!

Buck up

4. NCπ^o rate tuning

NCπ^o (neutral current π^o production)

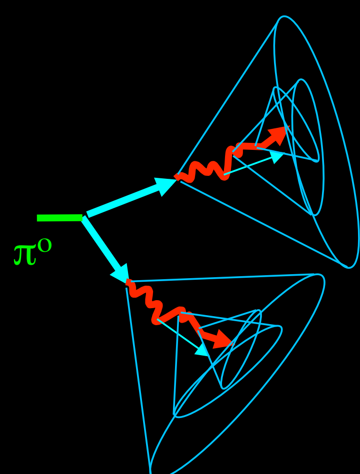
The signal of ν_e candidate is a single isolated electron

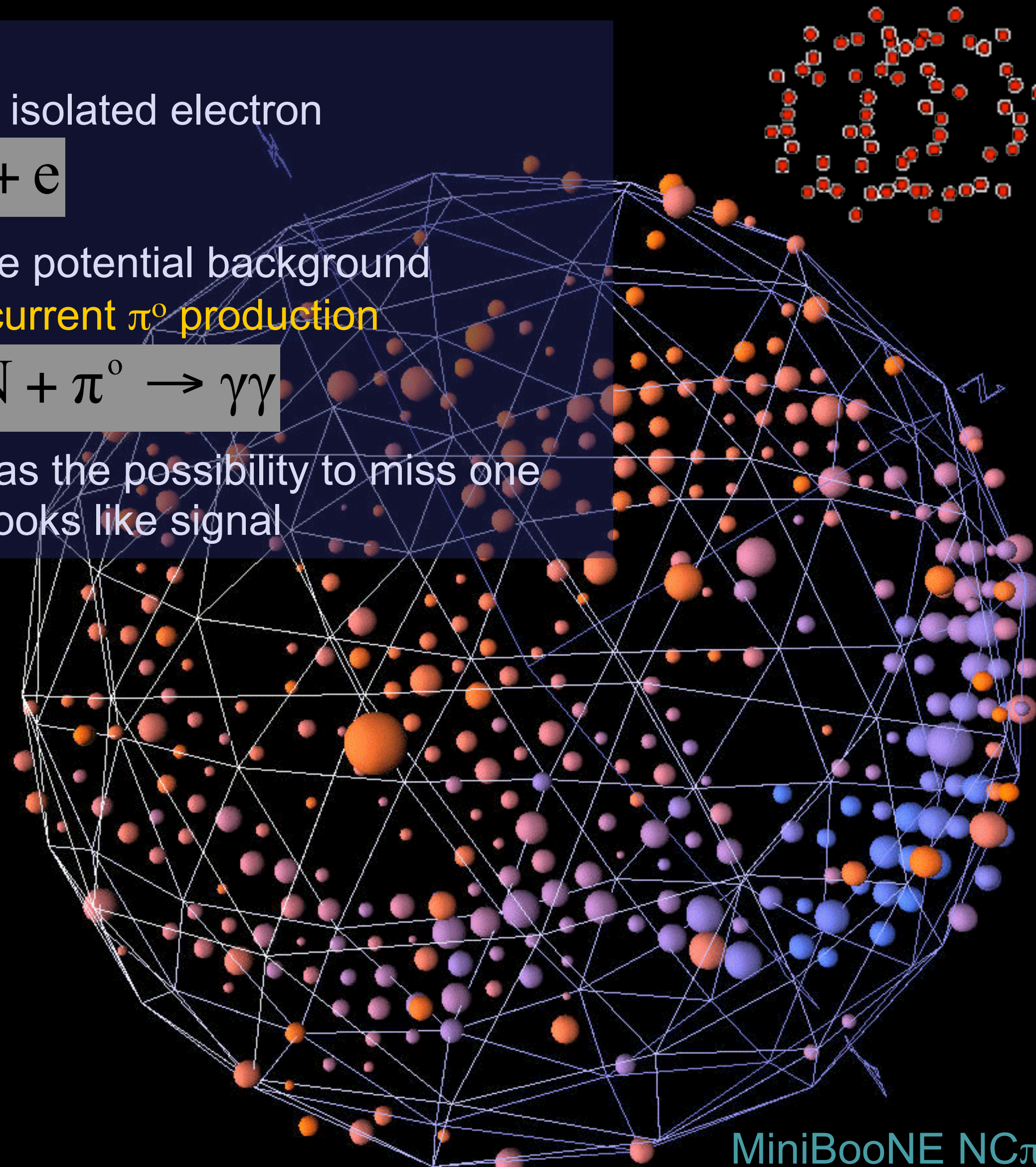
$$\nu_e + n \rightarrow p + e$$

- single electromagnetic shower is the potential background
- the notable background is Neutral current π^o production

$$\nu_\mu + N \rightarrow \nu_\mu + N + \pi^o \rightarrow \gamma\gamma$$

Because of kinematics, one always has the possibility to miss one gamma ray, and hence this reaction looks like signal





MiniBooNE NCπ^o candidate

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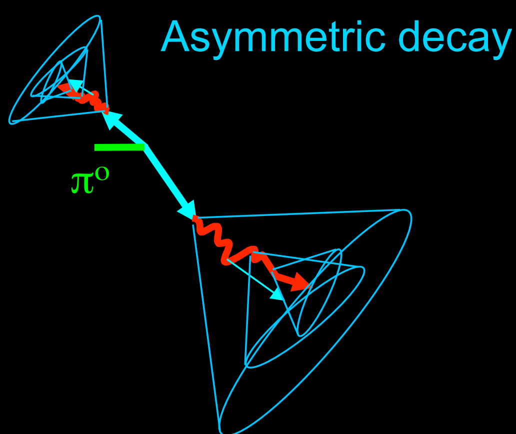
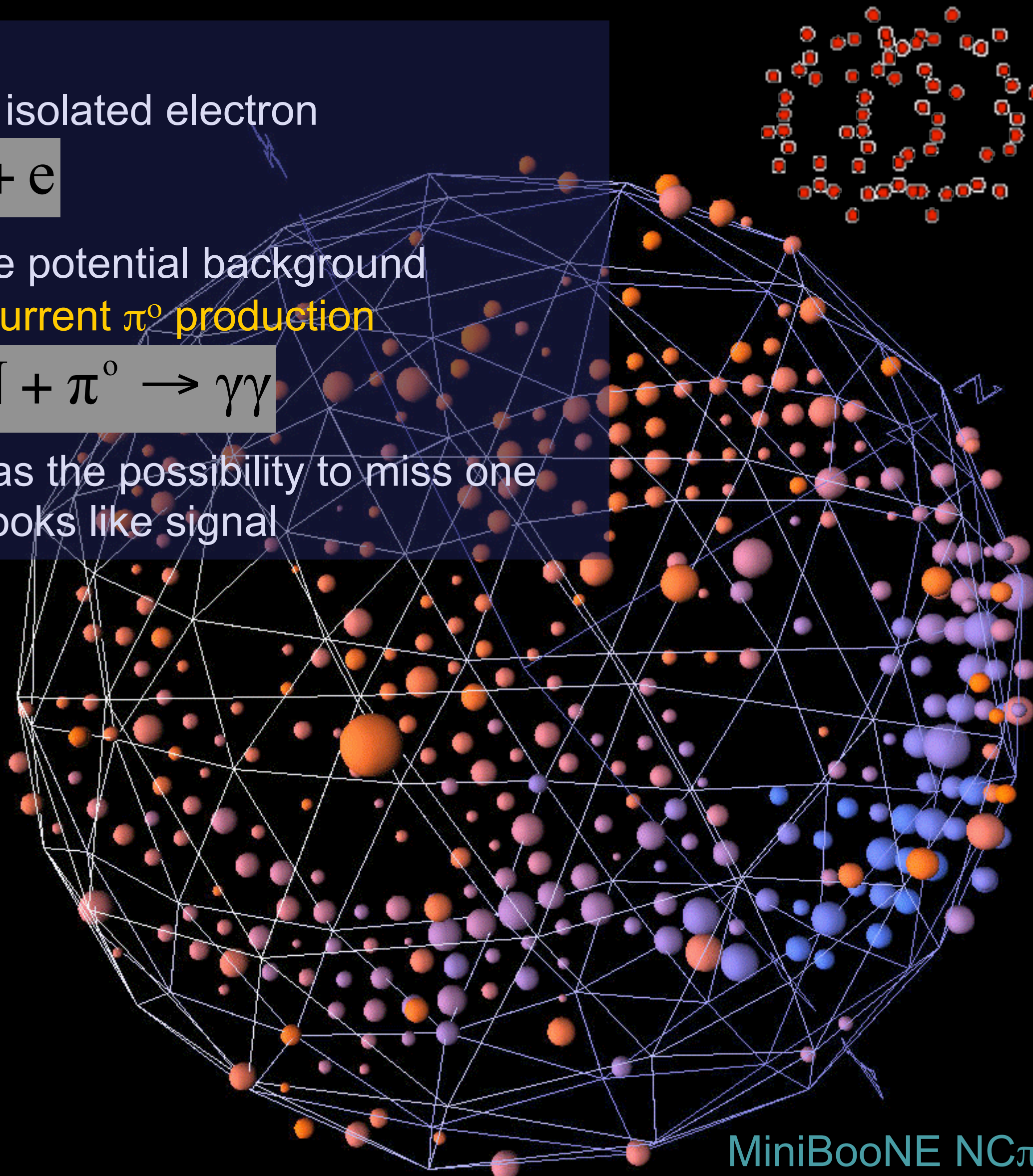
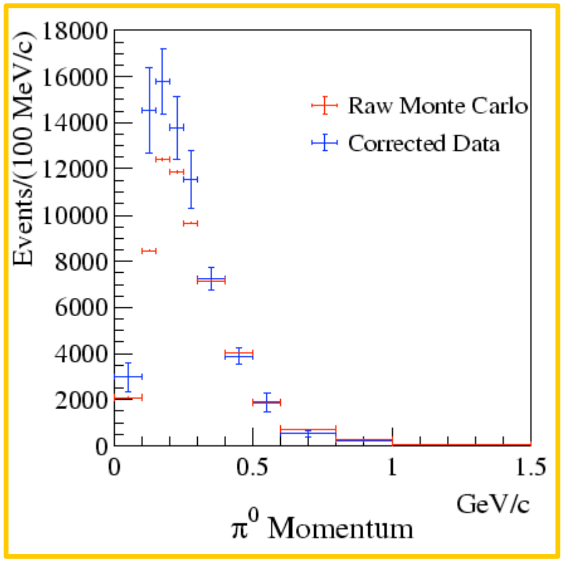




MiniBooNE NCπ^o candidate

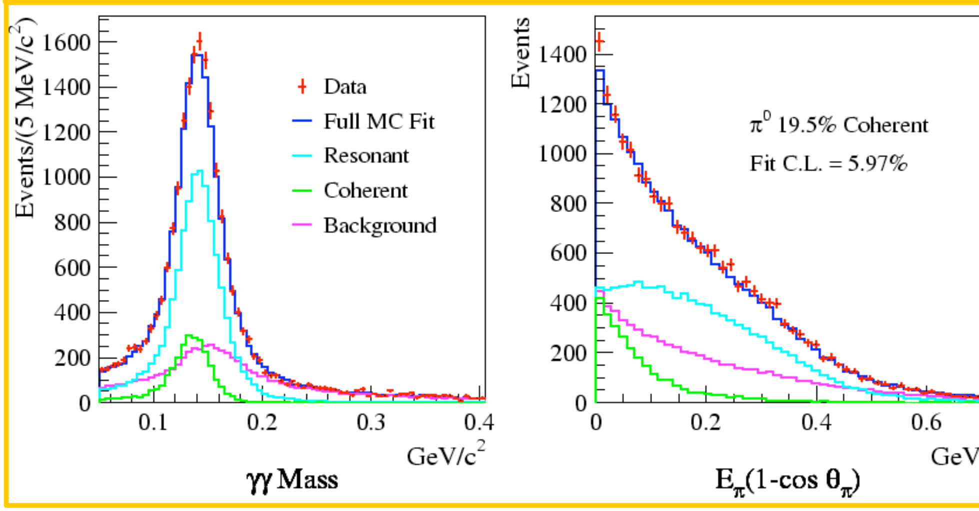
4. NCπ^o rate tuning

We tuned NCπ^o rate from our NCπ^o measurement. Since loss of gamma ray is pure kinematic effect, after tuning we have a precise prediction for intrinsic NCπ^o background for ν_e appearance search.



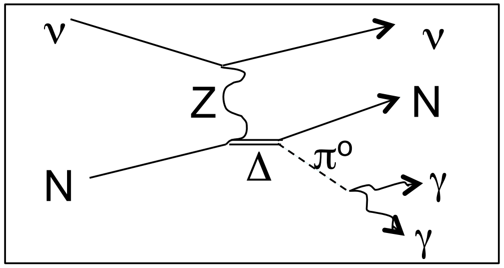
MiniBooNE collaboration
PLB664(2008)41

Data-Mc comparison of π^o kinematics (after tuning)



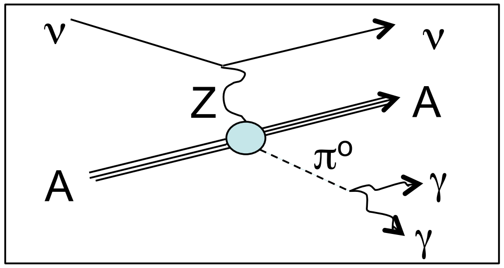
Resonance

$$\nu_\mu + N \rightarrow \nu_\mu + N + \pi^o$$

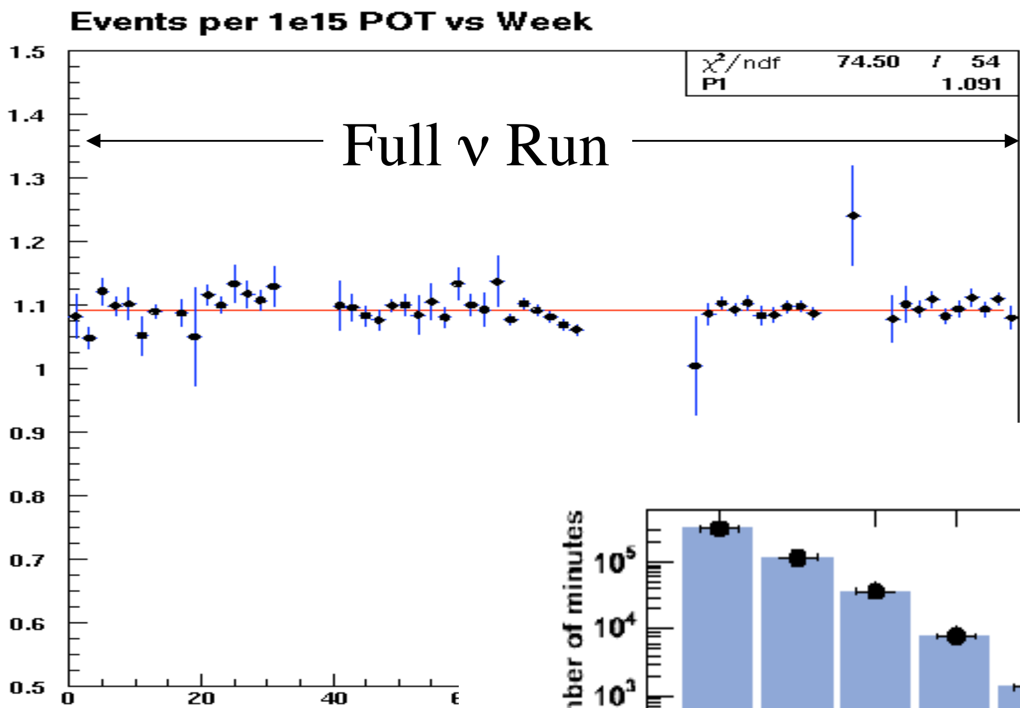


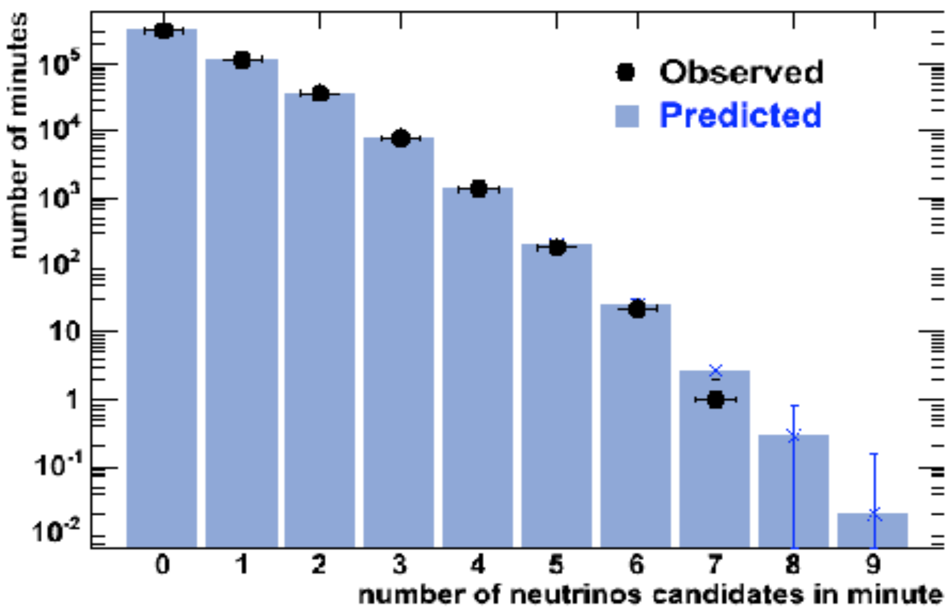
Coherent

$$\nu_\mu + A \rightarrow \nu_\mu + A + \pi^o$$



3. Stability of running



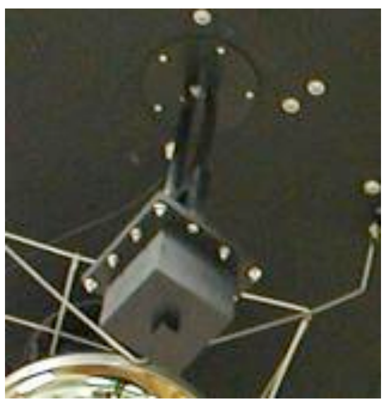


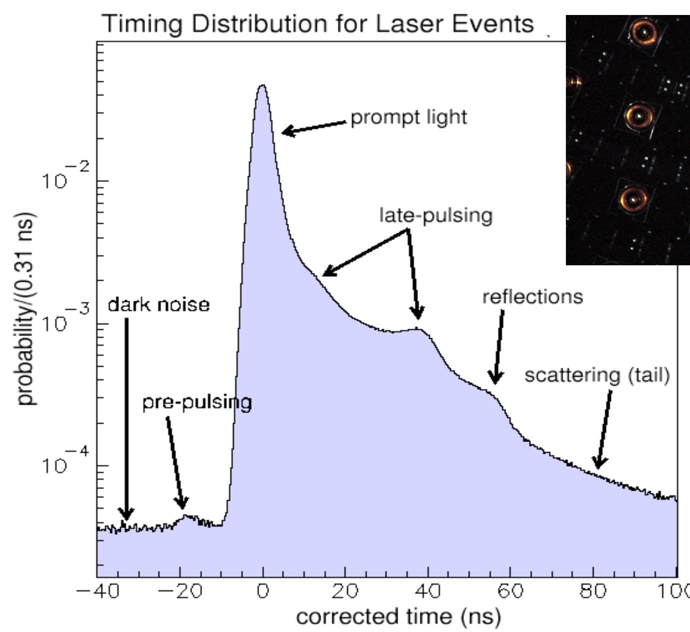
Observed and expected events per minute

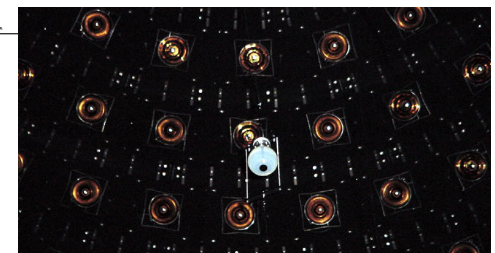
4. Calibration source

Laser flask system

Muon tracker and scintillation cube system







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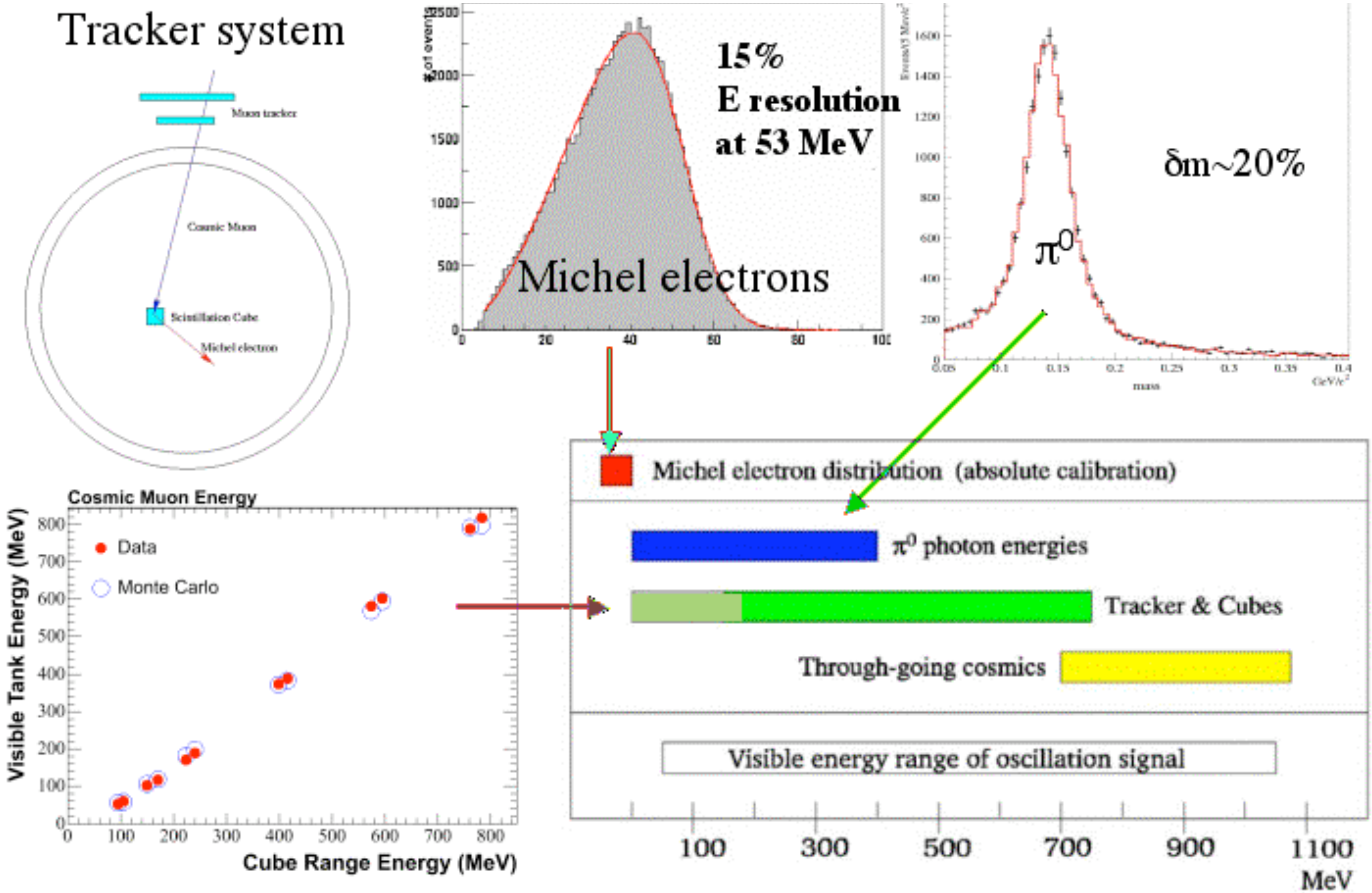
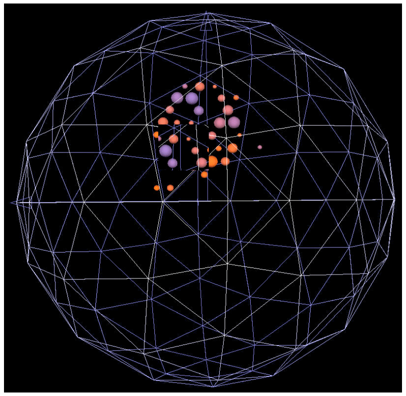


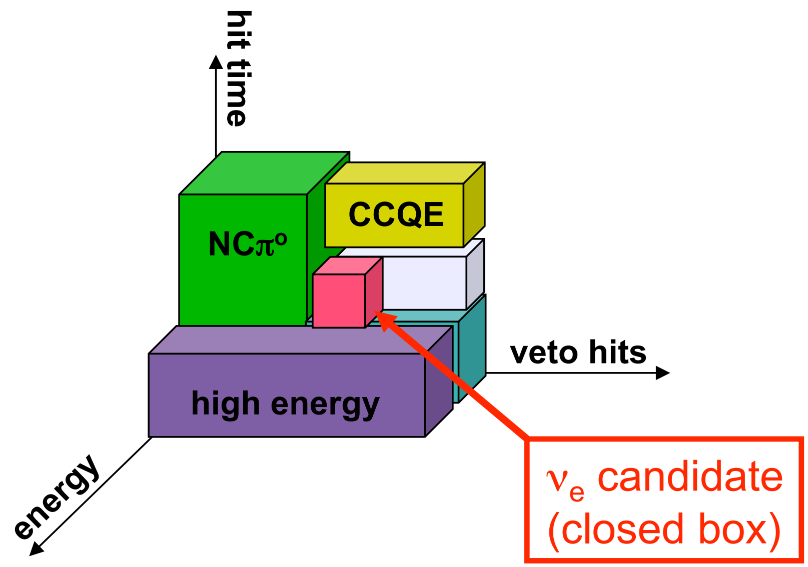
5. Blind analysis

$$\nu_e + n \rightarrow p + e^-$$
$$(\nu_e + {}^{12}C \rightarrow X + e^-)$$



The MiniBooNE signal is small but relatively easy to isolate

The data is described in n-dimensional space;

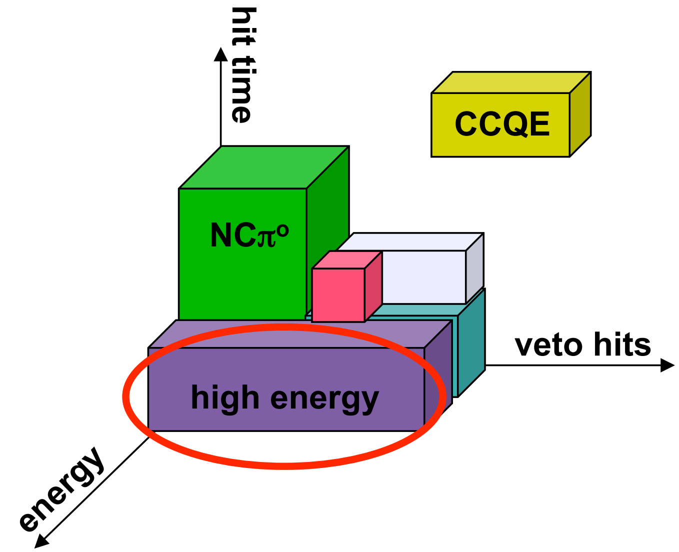


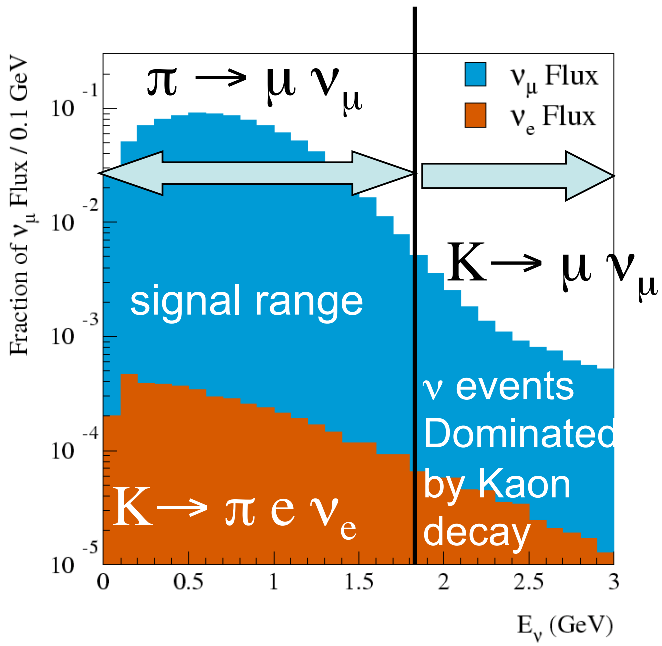
The data is classified into "box". For boxes to be "opened" to analysis they must be shown to have a signal < 1σ. In the end, 99% of the data were available
(boxes need not to be exclusive set)

5. Blind analysis

(2) measure high energy ν_μ events to constraint ν_e background from K decay

At high energies, above “signal range” ν_μ and “ν_e -like” events are largely due to kaon decay





example of open boxes;
- ν_μCCQE
- high energy event
- CCπ^+
- NC elastics
- NC π^o
- NC electron scattering
- Michel electron

etc....

5. MiniBooNE oscillation analysis structure

Start with a GEANT4 flux prediction for the ν spectrum from π and K produced at the target

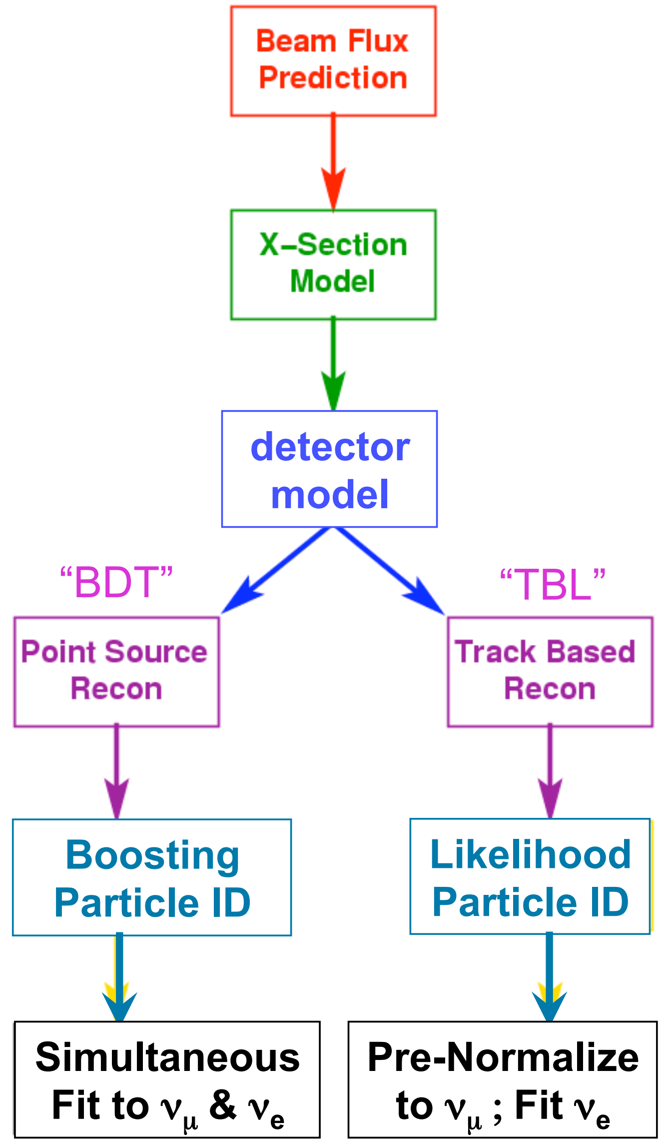
Predict ν interactions using NUANCE neutrino interaction generator

Pass final state particles to GEANT3 to model particle and light propagation in the tank

Starting with event reconstruction, independent analyses form: (1) Track Based Likelihood (TBL) and (2) Boosted Decision Tree (BDT)

Develop particle ID/cuts to separate signal from background

Fit reconstructed E_ν^{QE} spectrum for oscillations

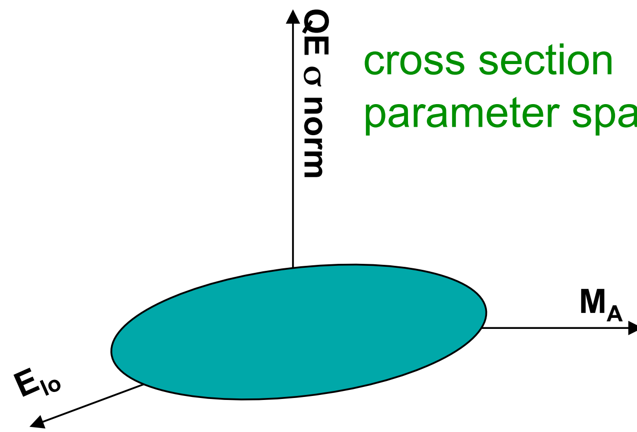


5. Multisim

ex) cross section uncertainties

M_A^{QE}	6%	correlated
E_{lo}^{sf}	2%	
QE σ norm	10%	uncorrelated

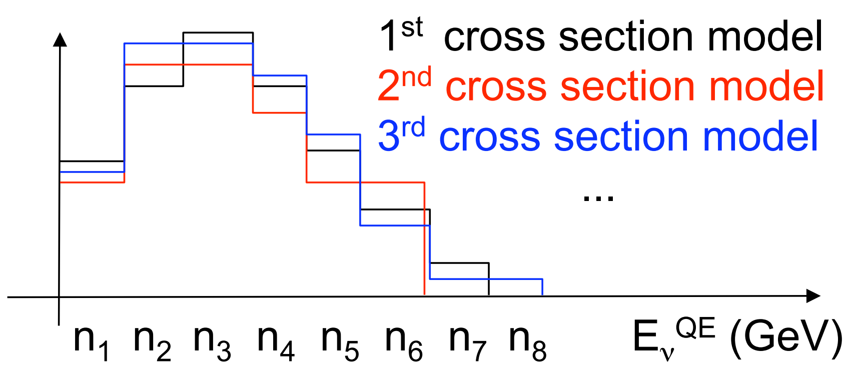
cross section parameter space



Input cross section error matrix

$$M_{input}(xs) = \begin{pmatrix} var(M_A) & cov(M_A, E_{lo}) & 0 \\ cov(M_A, E_{lo}) & var(E_{lo}) & 0 \\ 0 & 0 & var(\sigma - norm) \end{pmatrix}$$

cross section error for E_ν^{QE}

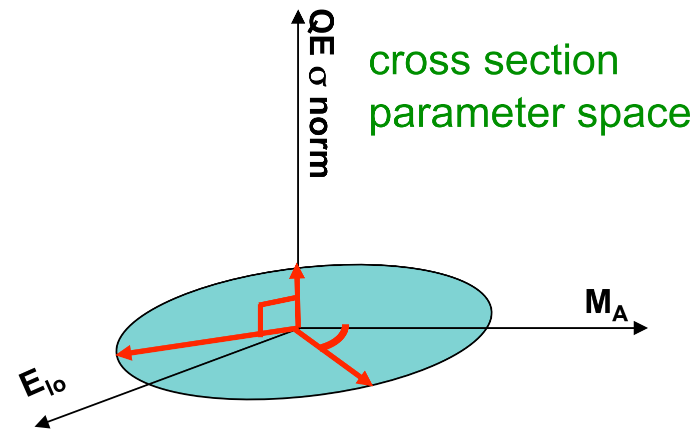


repeat this exercise many times to create smooth error matrix for E_ν^{QE}

5. Multisim

ex) cross section uncertainties

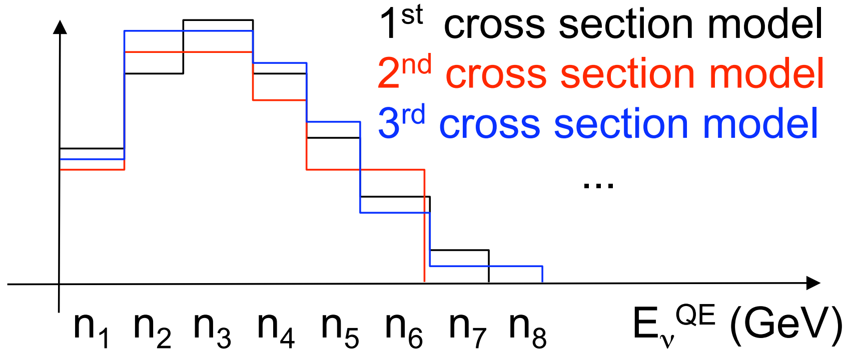
M_A^{QE}	6%	correlated
E_{lo}^{sf}	2%	
QE σ norm	10%	uncorrelated



Input cross section error matrix

$$M_{input}(xs) = \begin{pmatrix} var(M_A) & cov(M_A, E_{lo}) & 0 \\ cov(M_A, E_{lo}) & var(E_{lo}) & 0 \\ 0 & 0 & var(\sigma - norm) \end{pmatrix}$$

cross section error for E_ν^{QE}



repeat this exercise many times to create smooth error matrix for E_ν^{QE}

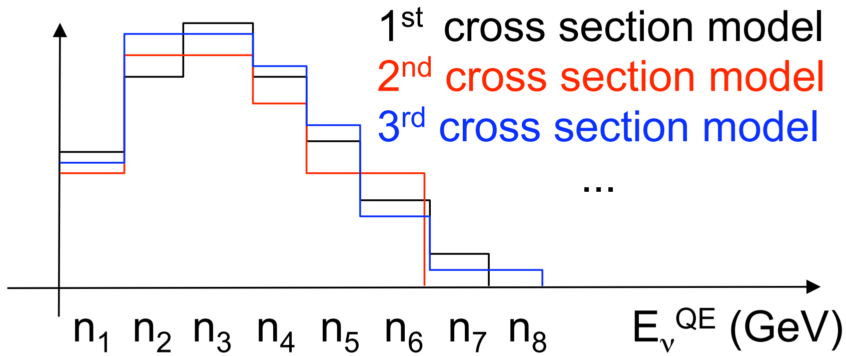
5. Multisim

Output cross section error matrix for E_ν^{QE}

$$\left[M_{output}(xs)\right]_{ij} \approx \frac{1}{S}\sum_{k}^{S}\left(N_i^k(xs) - N_i^{MC}\right)\left(N_j^k(xs) - N_j^{MC}\right)$$

$$M_{output}(xs) = \begin{pmatrix} var(n_1) & cov(n_1,n_2) & cov(n_1,n_3) & \cdots \\ cov(n_1,n_2) & var(n_2) & cov(n_2,n_3) & \cdots \\ cov(n_1,n_3) & cov(n_2,n_3) & var(n_3) & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

cross section error for E_ν^{QE}



Oscillation analysis use output error matrix for χ^2 fit;

$$\chi^2 = (\text{data - MC})^T (M_{output})^{-1} (\text{data - MC})$$

5. Multisim

ex) cross section uncertainties

M_A^{QE}	6%	determined from MiniBooNE ν_μ QE data
E_{lo}^{sf}	2%	
QE σ norm	10%	
QE σ shape	function of E_ν	
ν_e/ν_μ QE σ	function of E_ν	

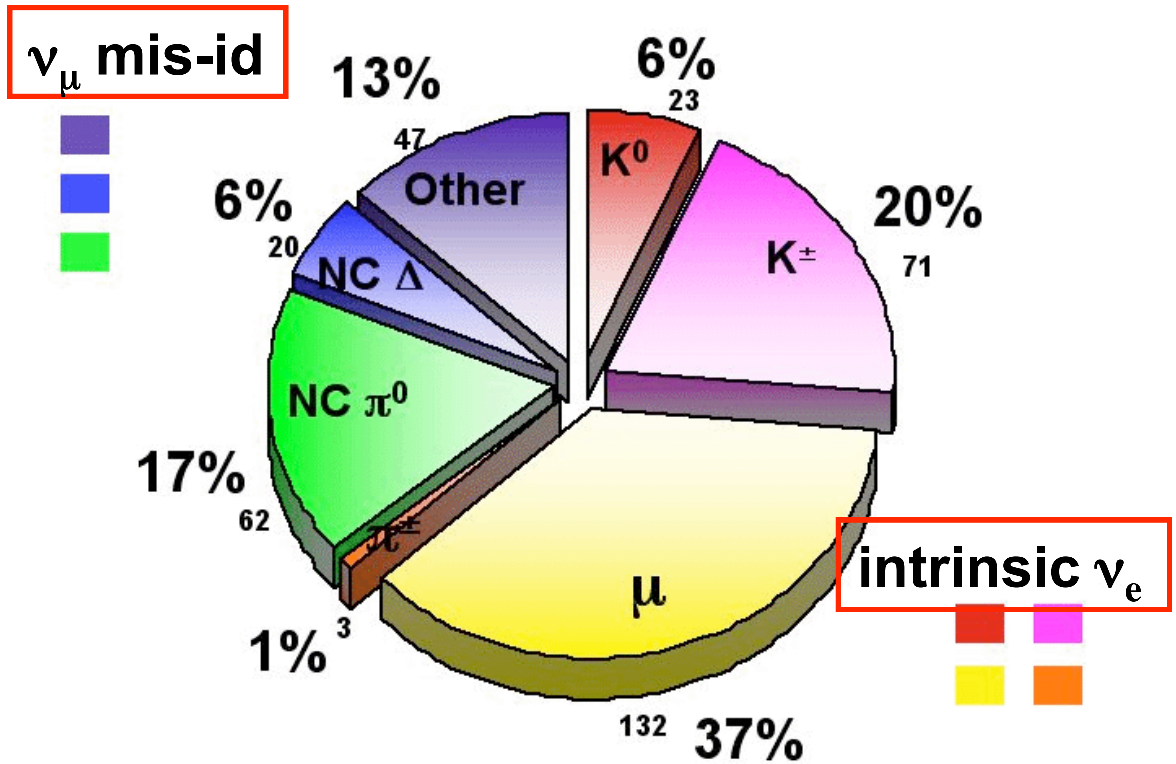
NC π^0 rate	function of π^0 mom	determined from MiniBooNE ν_μ NC π^0 data
M_A^{coh}, coh σ	±25%	
$\Delta \to N\gamma$ rate	function of γ mom + 7% BF	

E_B, p_F	9 MeV, 30 MeV	determined from other experiments
Δs	10%	
$M_A^{1\pi}$	25%	
$M_A^{N\pi}$	40%	
DIS σ	25%	

etc...

5. Oscillation analysis background summary

We have two categories of backgrounds:



7. Multisim

Error Matrix Elements:

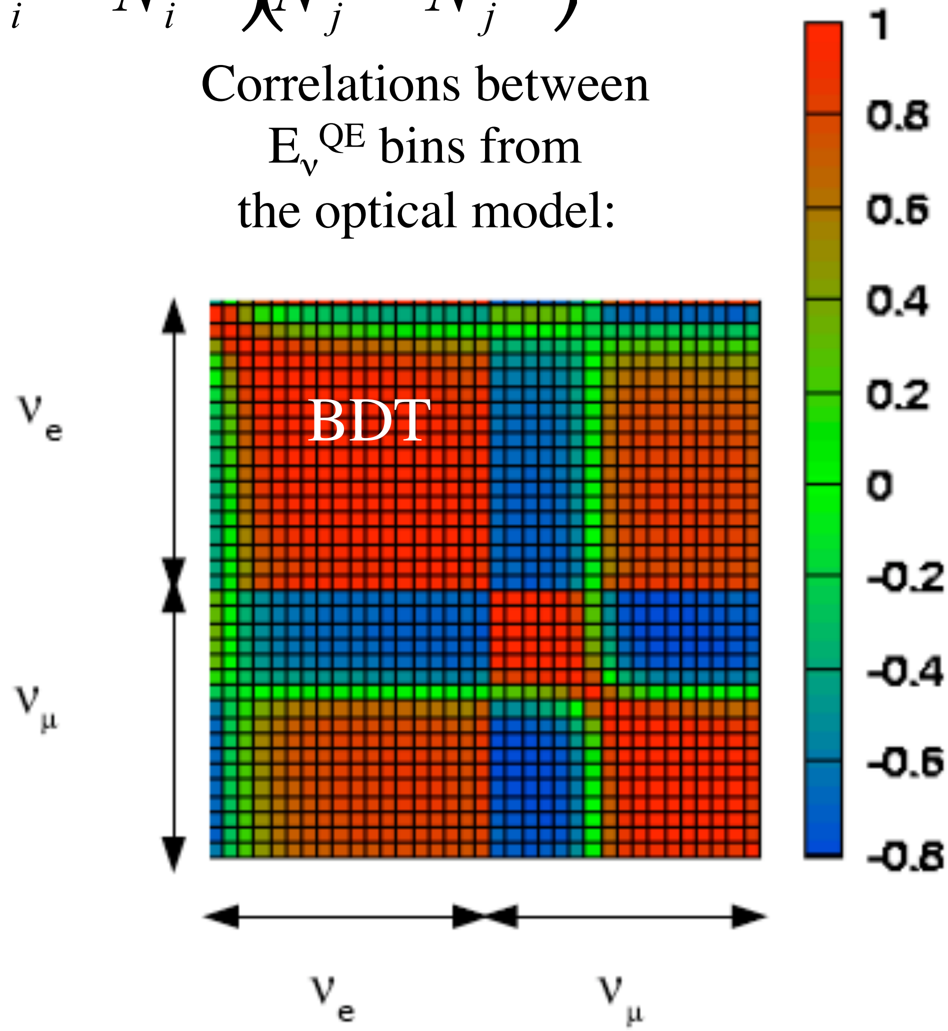
$$E_{ij} \approx \frac{1}{M}\sum_{\alpha=1}^{M}\left(N_i^{\alpha} - N_i^{MC}\right)\left(N_j^{\alpha} - N_j^{MC}\right)$$

- N is number of events passing cuts
- MC is standard monte carlo
- α represents a given multisim
- M is the total number of multisims
- i,j are E_ν^{QE} bins

Total error matrix
is sum from each source.

TB: ν_e-only total error matrix
BDT: ν_μ-ν_e total error matrix

Correlations between
E_ν^{QE} bins from
the optical model:

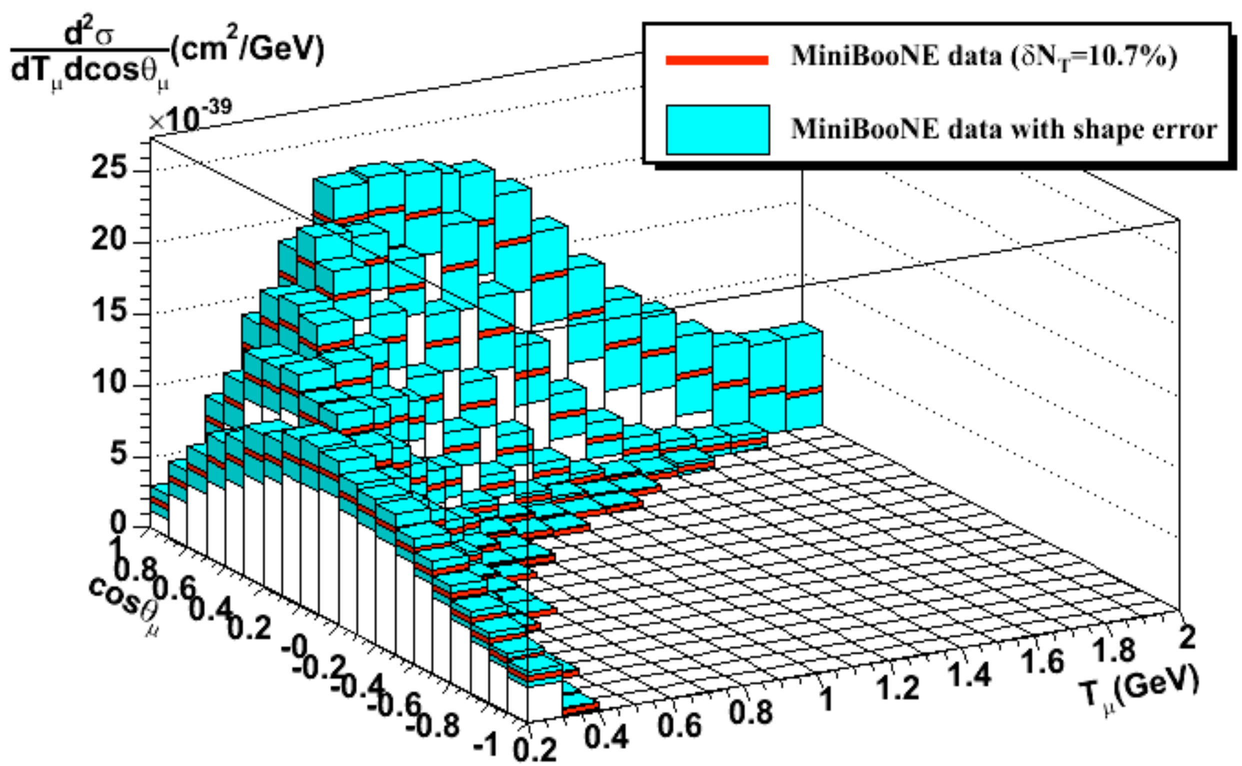


6. CCQE double differential cross section

Flux-integrated double differential cross section (T_μ-$\cos\theta$)

This is the most complete information about neutrino cross section based on muon kinematic measurement.

The error shown here is shape error, a total normalization error (δN_T=10.7%) is separated.



6. Paradigm shift in neutrino cross section!?

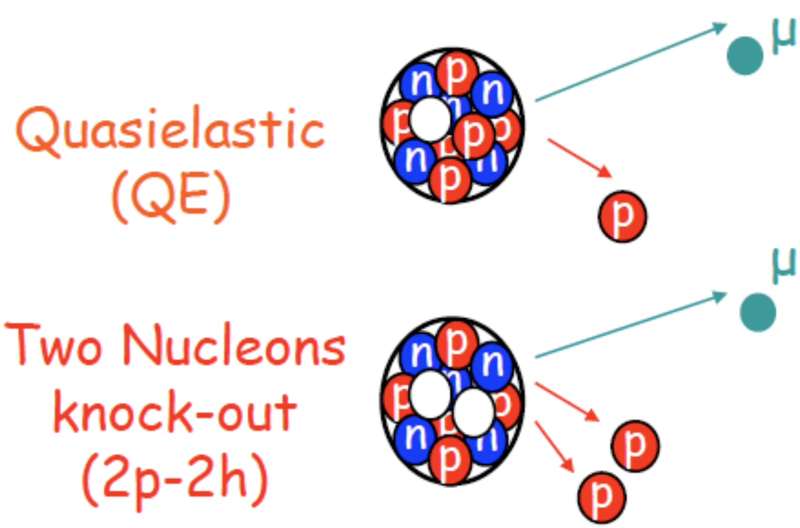
Martini et al

Theoretical approaches for the large cross section and harder Q^2 spectrum

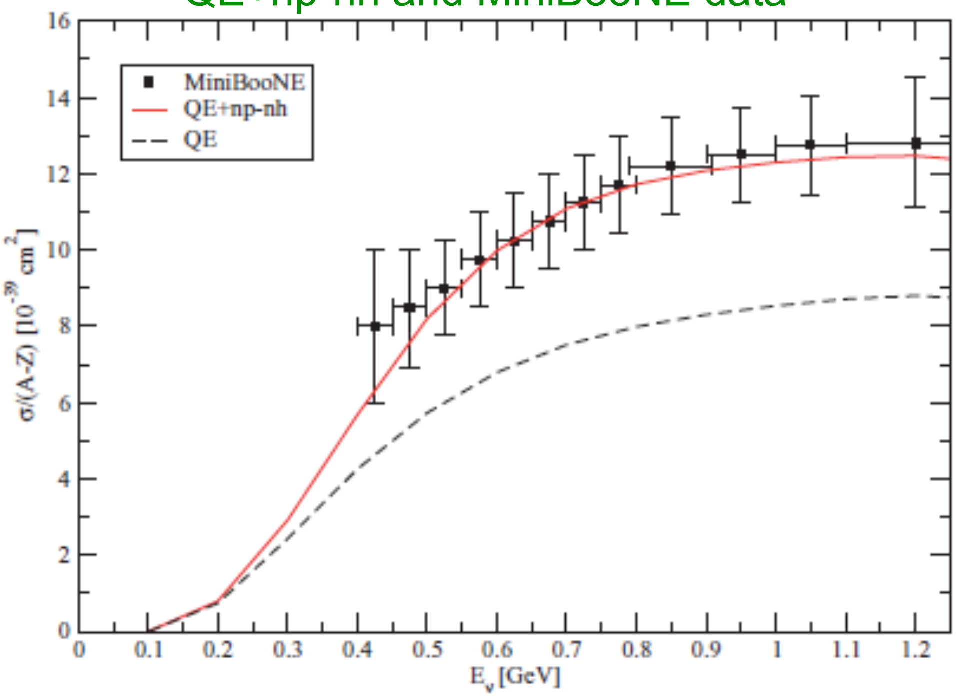
RPA formalism
SRC+MEC

Martini et al.,PRC80(2009)065501
Carlson et al.,PRC65(2002)024002

The presence of a polarization cloud (tensor interaction) surrounding a nucleon in the nuclear medium contribute large 2p-2h interaction. Since MiniBooNE counts multi nucleon emission as CCQE, 2p-2h interaction is counted as CCQE and it enhances CCQE more than 40%.



QE+np-nh and MiniBooNE data



6. Paradigm shift in neutrino cross section!?

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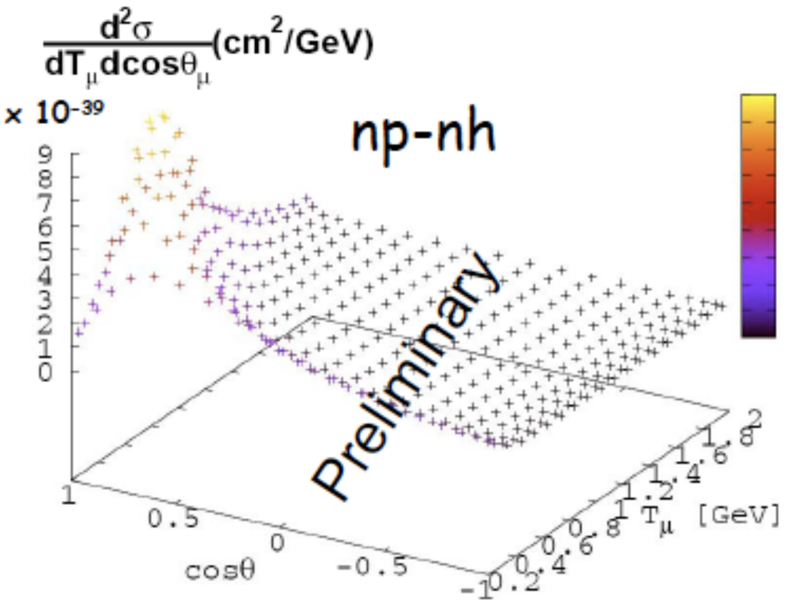
Theoretical approaches for the large cross section and harder Q^2 spectrum

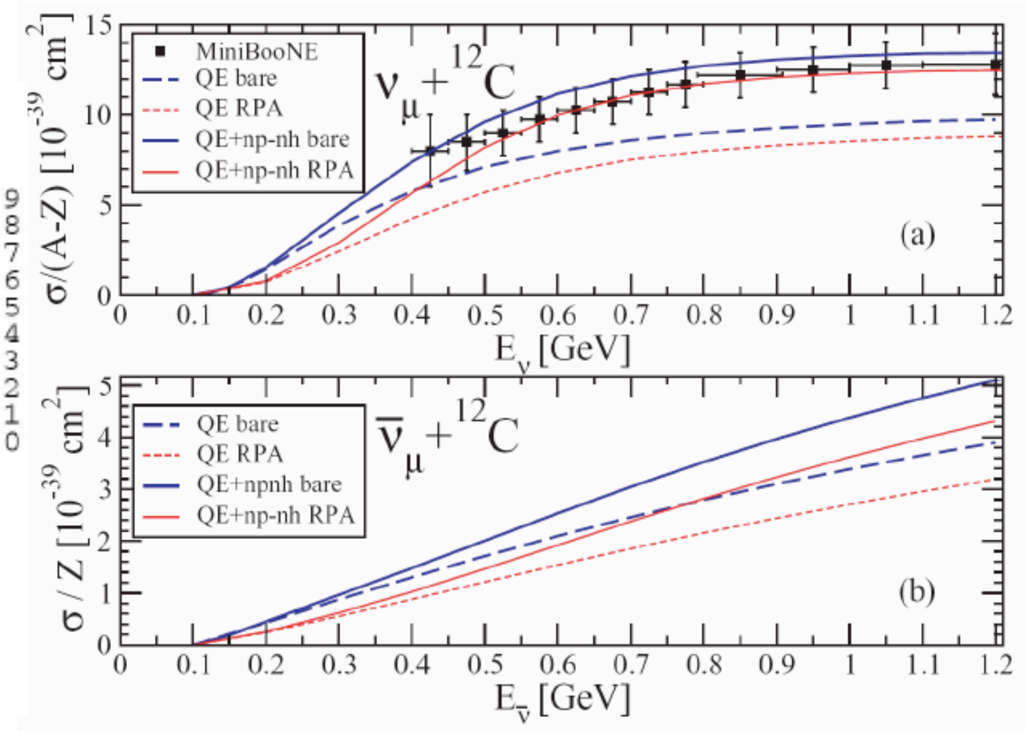
RPA formalism
SRC+MEC

Martini et al.,PRC80(2009)065501
Carlson et al.,PRC65(2002)024002

- One can test the detail of this model with the double differential cross section.
- The role of np-nh interaction is smaller to antineutrino channel.
- Sept. 30 11:00am (CDT), video lecture by Martini (510.883.7860 ID 8577368#)

np-nh double differential cross section





6. Paradigm shift in neutrino cross section!?

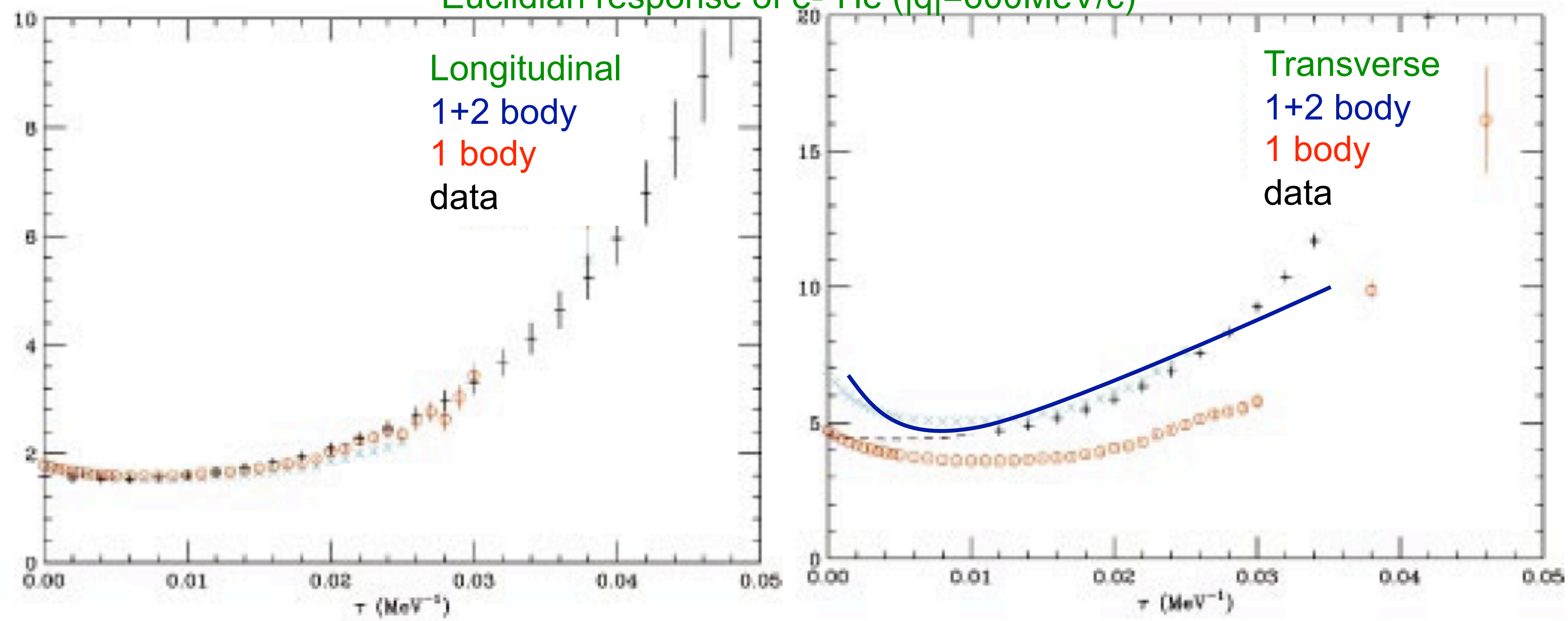
Theoretical approaches for the large cross section and harder Q^2 spectrum

RPA formalism
SRC+MEC

Martini et al.,PRC80(2009)065501
Carlson et al.,PRC65(2002)024002

Transverse response is enhanced by presence of short range correlation (SRC) and 2-body current (meson exchange current, MEC).

Euclidian response of e-^{4}He (|q|=600MeV/c)



Jon Link, Nov. 18, 2005
Fermilab Wine & Cheese seminar

PHYSICAL REVIEW D VOLUME 23, NUMBER 11 1 JUNE 1981

Quasielastic neutrino scattering: A measurement of the weak nucleon axial-vector form factor

N. J. Baker, A. M. Cnops,* P. L. Connolly, S. A. Kahn, H. G. Kirk, M. J. Murtagh, R. B. Palmer, N. P. Samios, and M. Tanaka

Brookhaven National Laboratory, Upton, New York 11973

(Received 12 February 1981)

Brookhaven AGS

7ft D_2 Bubble Chamber

The quasielastic reaction $\nu_\mu n \to \mu^- p$ was studied in an experiment using the BNL 7-foot deuterium bubble chamber exposed to the wide-band neutrino beam with an average energy of 1.6 GeV. A total of 1138 quasielastic events in the momentum-transfer range $Q^2 = 0.06-3.00$ $(\mathrm{GeV}/c)^2$ were selected by kinematic fitting and particle identification and were used to extract the axial-vector form factor $F_A(Q^2)$ from the Q^2 distribution. In the framework of the conventional $V-A$ theory, we find that the dipole parametrization is favored over the monopole. The value of the axial-vector mass M_A in the dipole parametrization is 1.07 ± 0.06 GeV, which is in good agreement with both recent neutrino and electroproduction experiments. In addition, the standard assumptions of conserved vector current and no second-class currents are checked.

We have used a maximum likelihood method to extract M_A from the shape of the Q^2 distribution for each observed neutrino energy. This likelihood function $\mathfrak{L}^I$ is independent of the shape of the neutrino spectrum ...

They didn't even try to determine their ν flux from pion production and beam dynamics.

Phys. Rev. D **25**, 617 (1982)

The distribution of events in neutrino energy for the 3C $\nu d \to \mu^- p p_s$ events is shown in Fig. 4 together with the quasielastic cross section $\sigma(\nu n \to \mu^- p)$ calculated using the standard $V-A$ theory with $M_A = 1.05 \pm 0.05$ GeV and $M_V = 0.84$ GeV. The absolute cross sections for the CC interactions have been measured using the quasielastic events and its known cross section.[4]

In subsequent cross section analyses the theoretical ("known") quas-ielastic cross section and observed quasi-elastic events were used to determine the flux.

Jon Link, Nov. 18, 2005
Fermilab Wine & Cheese seminar

VOLUME 49, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JULY 1982

Fermilab
15ft D_2 Bubble Chamber

Neutrino Flux and Total Charged-Current Cross Sections in High-Energy Neutrino-Deuterium Interactions

T. Kitagaki, S. Tanaka, H. Yuta, K. Abe, K. Hasegawa, A. Yamaguchi, K. Tamai, T. Hayashino, Y. Ohtani, and H. Hayano
Tohoku University, Sendai 980, Japan

To obtain the total cross section from the number of events, the neutrino flux has to be measured on an absolute scale. In this analysis, we determine the neutrino flux using 362 quasielastic events identified in our data[10] and the cross section for reaction (2) derived from the $V-A$ theory.

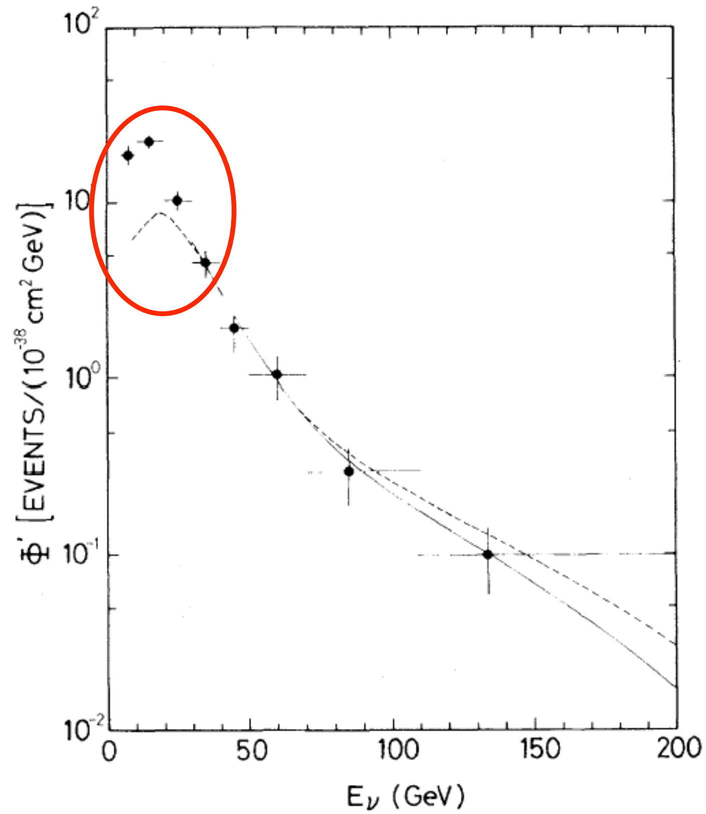


FIG. 2. Neutrino flux distribution obtained from the quasielastic events and the predicted cross section with $M_A = 1.05$ GeV. The solid curve is obtained from the best fit to the flux data for $E_\nu > 30$ GeV. The dashed curve is taken from the Monte Carlo simulation of the flux.

Again, they use QE events and theoretical cross section to calculate the ν.

When they try to get the flux from meson (π and K) production and decay kinematics they fail miserably for E_ν<30 GeV.

Jon Link, Nov. 18, 2005
Fermilab Wine & Cheese seminar

PHYSICAL REVIEW D VOLUME 34, NUMBER 1 1 JULY 1986

Determination of the neutrino fluxes in the Brookhaven wide-band beams

L. A. Ahrens, S. H. Aronson, P. L. Connolly,* B. G. Gibbard, M. J. Murtagh, S. J. Murtagh,† S. Terada, and D. H. White
Physics Department, Brookhaven National Laboratory, Upton, New York 11973

Brookhaven AGS

Liquid Scintillator

The beam calculations described here were based on the Grote, Hagedorn, and Ranft (GHR) (Ref. 11) parametrization; that of Sanford and Wang was used for comparison. An estimate was made of pion production by reinteracting protons guided by the shape of the observed ν_μ spectrum and the observed angular distribution of muons from quasielastic events. The procedure is described[12] in the Appendix.

The Procedure

- Pion production cross sections in some low momentum bins are scaled up by 18 to 79%.
- The K^+ to π^+ ratio is increased by 25%.
- Overall neutrino (anti-neutrino) flux is increased by 10% (30%).

All driven by the neutrino events observed in the detector!

Jon Link, Nov. 18, 2005
Fermilab Wine & Cheese seminar

PHYSICAL REVIEW D VOLUME 16, NUMBER 11 1 DECEMBER 1977

Argonne ZGS
12ft D_2 Bubble Chamber

Study of neutrino interactions in hydrogen and deuterium: Description of the experiment and study of the reaction $\nu + d \to \mu^- + p + p_s$†

S. J. Barish,* J. Campbell,‡ G. Charlton,§ Y. Cho, M. Derrick, R. Engelmann,‖ L. G. Hyman, D. Jankowski, A. Mann,¶ B. Musgrave, P. Schreiner, P. F. Schultz, R. Singer, M. Szczekowski,** T. Wangler, and H. Yuta††
Argonne National Laboratory, Argonne, Illinois 60439

Flux derived from pion production data. Were able to test assumptions about the form of the cross section using absolute rate and shape information.

TABLE IV. Results of axial-form-factor fits.

Likelihood function	M_A^{Dipole} (GeV)	M_A^{Monopole} (GeV)	M_A^{Tripole} (GeV)
Rate	$0.75^{+0.13}_{-0.11}$	$0.45^{+0.11}_{-0.07}$	$0.96^{+0.17}_{-0.14}$
Shape	1.010 ± 0.09	0.56 ± 0.08	1.32 ± 0.11
Rate and shape	0.95 ± 0.09	0.52 ± 0.08	1.25 ± 0.11
Flux independent	0.95 ± 0.09	0.53 ± 0.08	1.25 ± 0.11

- Pion production measured in ZGS beams were used in this analysis
- A very careful job was done to normalize the beam.
- Yet they have a 25% inconsistency between the axial mass they measure considering only rate information verses considering only spectral information.

Interpretation: Their normalization is wrong.

0-2. NCE cross section in MiniBooNE

by Denis Perevalov

MiniBooNE collaboration, arXiv:1007.4730

$$\nu_\mu + p \rightarrow \nu_\mu + p$$

$$\nu_\mu + n \rightarrow \nu_\mu + n$$

NCE measurement and Δs

By definition, longitudinally polarized quark functions are normalized with axial vector nucleon matrix element.

$$\int_0^1 dx < N | \bar{u}\gamma_\mu\gamma_5 u - \bar{d}\gamma_\mu\gamma_5 d - \bar{s}\gamma_\mu\gamma_5 s | N > = < N | -G_A(Q^2)\gamma_\mu\gamma_5\tau_3 + G_A^s(Q^2)\gamma_\mu\gamma_5 | N >$$

Then, strange quark spin contribution in the nucleon (called Δs) gives simple connection of DIS and elastic scattering world.

$$\int_0^1 dx\Delta s(x) \equiv \Delta s \equiv G_A^s(Q^2 = 0)$$

Since Δs is the Q^2=0 limit of isoscalar axial vector form factor, it can be accessed by NCE scattering measurement.

However, measured Δs in HERMES semi-inclusive DIS measurement (~0) and BNLE734 neutrino NCE measurement (~0.15) don't agree within their errors (so there is a great interest for the precise NCE measurement!).

by Denis Perevalov

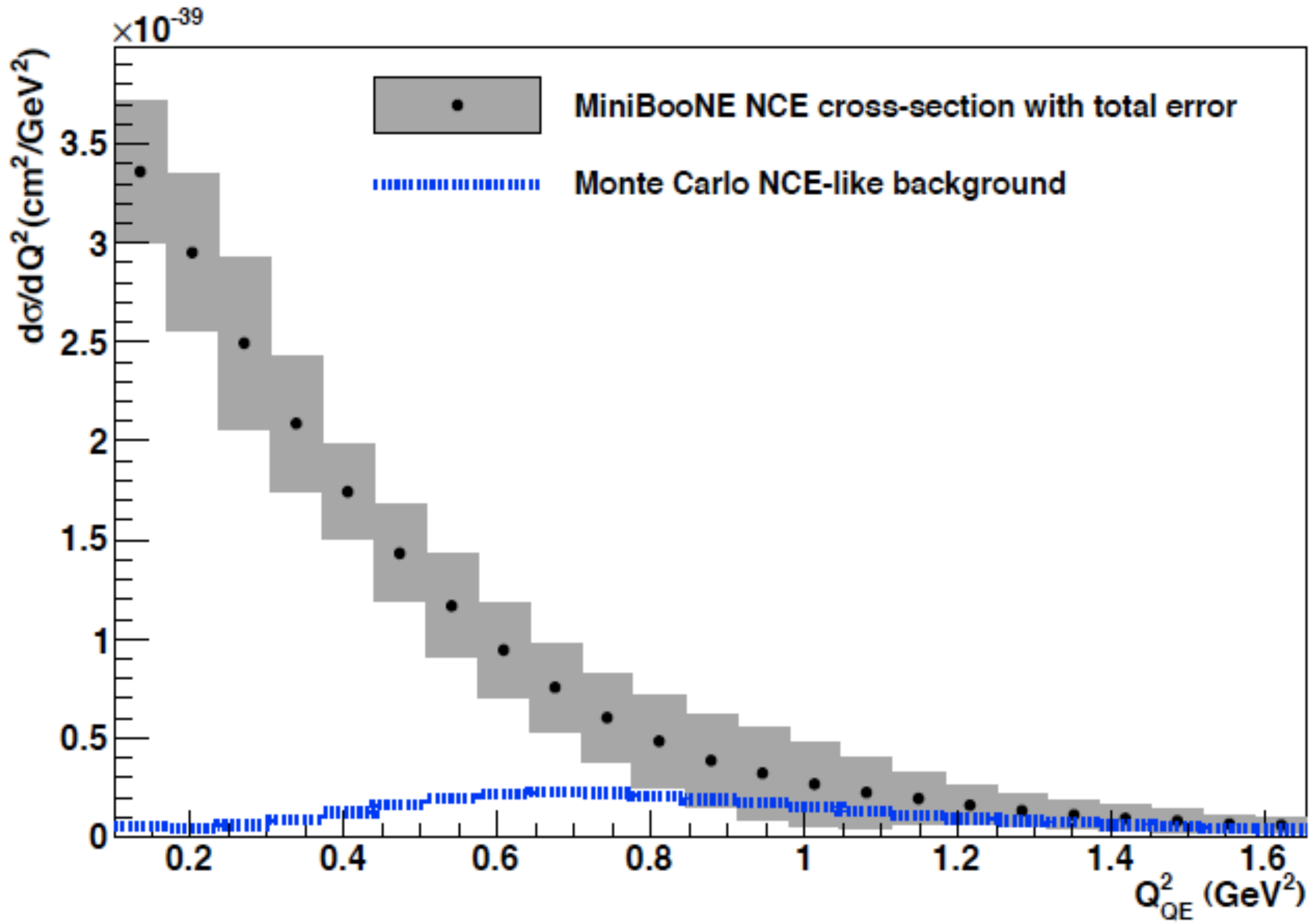
0-2. NCE cross section in MiniBooNE

Flux-averaged NCE p+n differential cross section

Measured cross section agree with BNLE734.

Intrinsic background prediction is also provided.

NCE data also prefer a controversial high M_A value.



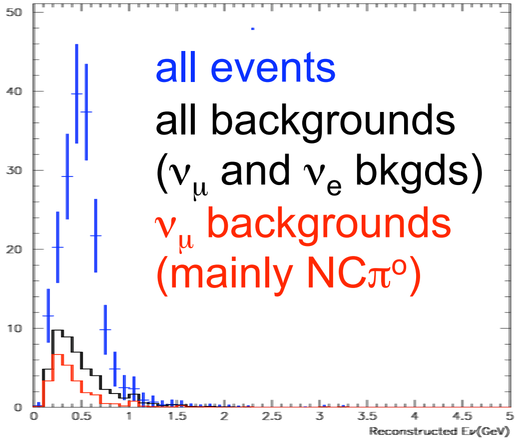
by Colin Anderson

0-3. NCπ^o cross section in MiniBooNE

$$\nu_\mu + N \to \nu_\mu + \Delta^o \to \nu_\mu + N + \pi^o$$
$$\nu_\mu + A \to \nu_\mu + A + \pi^o$$

MiniBooNE collaboration,
PRD81(2010)013005

ν_e candidate after 5 yrs at T2K ($\sin^2 2\theta_{13}$=0.1)



NCπ^o as a background of oscillation

π^o is notoriously known intrinsic misID of ν_e appearance ($\sim\theta_{13}$) search long baseline neutrino oscillation experiments. So we need to understand kinematics carefully.

$$\nu_\mu \xrightarrow{\text{oscillation}} \nu_e + n \to p + e \to e - \text{like} \quad \text{(signal)}$$

$$\nu_\mu + N \to \nu_\mu + N + \pi^o \to \gamma + \cancel{\gamma} \to e - \text{like} \quad (\nu_\mu \text{background})$$

NCπ^o event definition

NCπ^o event is defined as NC interaction with one π^o exiting nuclei and no other mesons.
- This definition includes π^o production by final state interactions (FSIs).
- This definition excludes NCπ^o interaction when π^o is lost by FSIs.

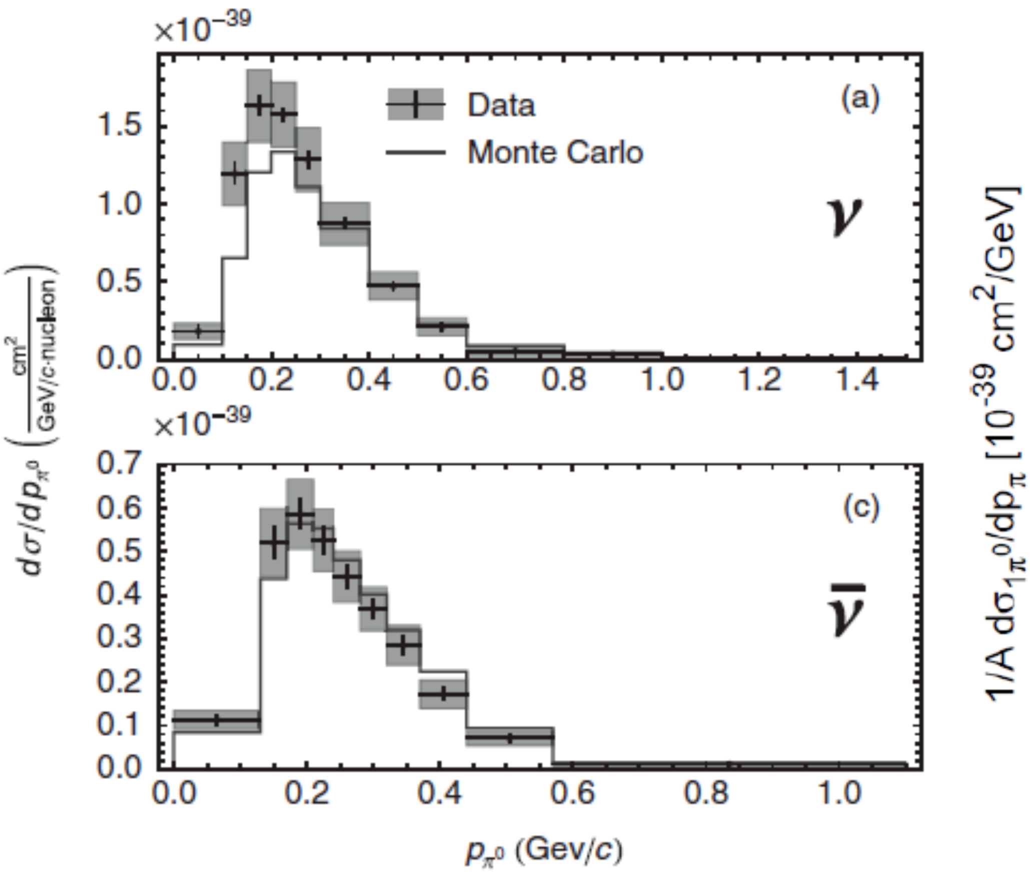
This is the necessary definition for the theorists to understand final state interactions (FSIs) without biases.

by Colin Anderson

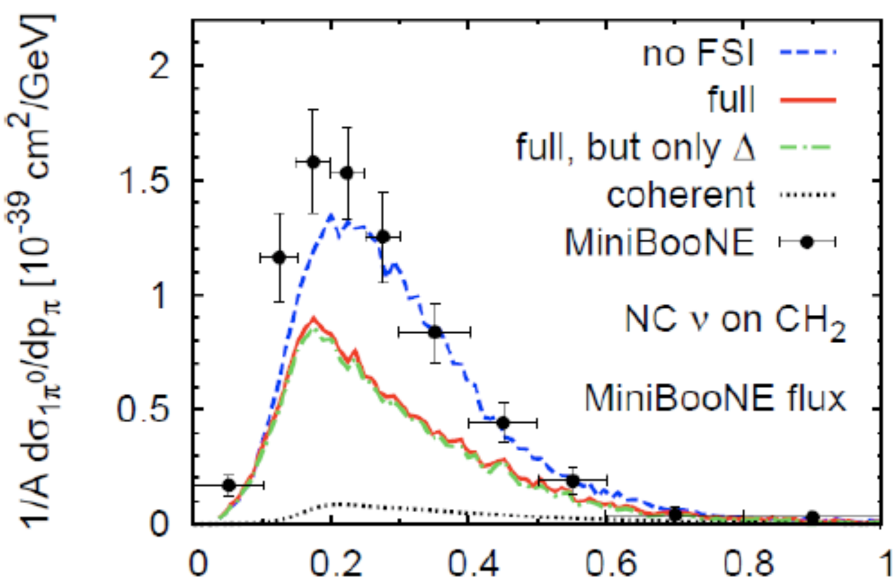
0-3. NCπ^o cross section in MiniBooNE

NCπ^o differential cross section

- Measurement is done both ν and anti-ν mode.
- This is the first measurement of NCπ^o production differential cross section.
- Theoretical model under-predicts nearly factor 2



GiBUU vs MiniBooNE
Tina Leitner, PhD thesis



by Mike Wilking

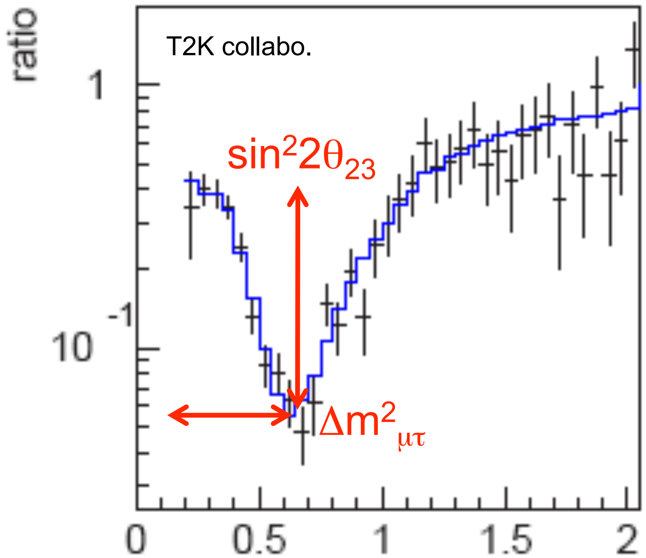
0-4. CCπ^+ cross section in MiniBooNE

MiniBooNE collaboration, paper in preparation

$$\nu_\mu + p(n) \rightarrow \mu + \Delta^{+(+)} \rightarrow \mu + p(n) + \pi^+$$
$$\nu_\mu + A \rightarrow \mu + A + \pi^+$$

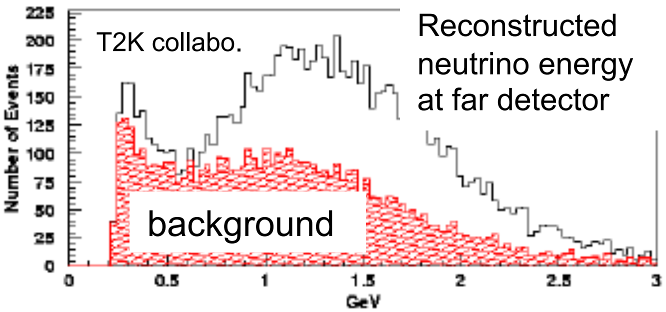
CCπ^+ event as a background of CCQE events

CCπ^+ event without pion is the intrinsic background for CCQE in Super-K. Therefore we need a good understanding of CCπ^+ kinematics comparing with CCQE for a better energy reconstruction (= better oscillation measurement).



Reconstructed neutrino energy (GeV)

mis-reconstruction of neutrino energy by misunderstanding of CCπ^+ events spoils ν_μ disappearance signals



by Mike Wilking

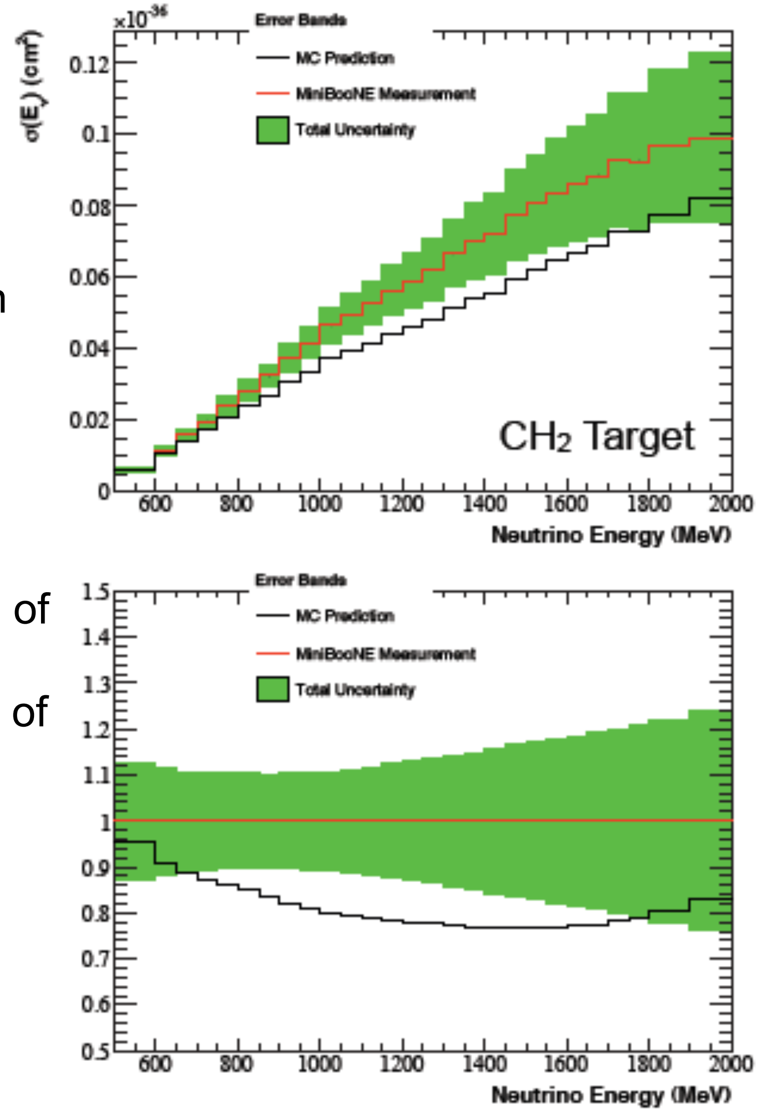
0-4. CCπ^+ cross section in MiniBooNE

CCπ^+ cross section

- After the cut, there is ~48,000 events with 90% purity, and correct pion/muon identification rate is 88%.
- data is higher than Rein-Sehgal model prediction (M_A=1.1GeV) over 20%.

Following 8 cross sections are measured.

- $\sigma(E_\nu)$: total cross section with function of E_ν
- $d\sigma/dQ^2$: differential cross section of Q^2
- $d^2\sigma/dT_\mu/d\cos\theta_\mu$: double differential cross section of muon kinematics
- $d^2\sigma/dT_\pi/d\cos\theta_\pi$: double differential cross section of pion kinematics



by Bob Nelson

MiniBooNE collaboration, paper in preparation

0-5. CCπº cross section in MiniBooNE

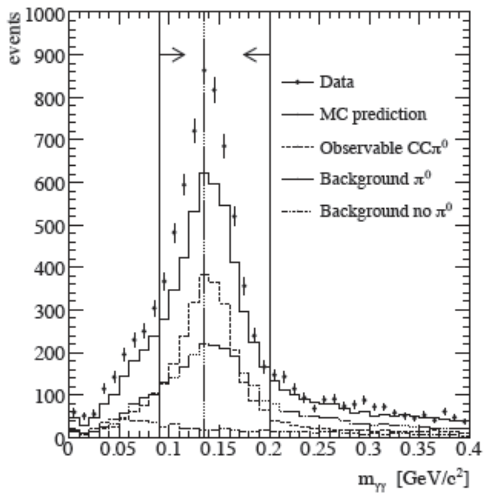
$$\nu_\mu + n \rightarrow \mu + \Delta^+ \rightarrow \mu + p + \pi^o$$

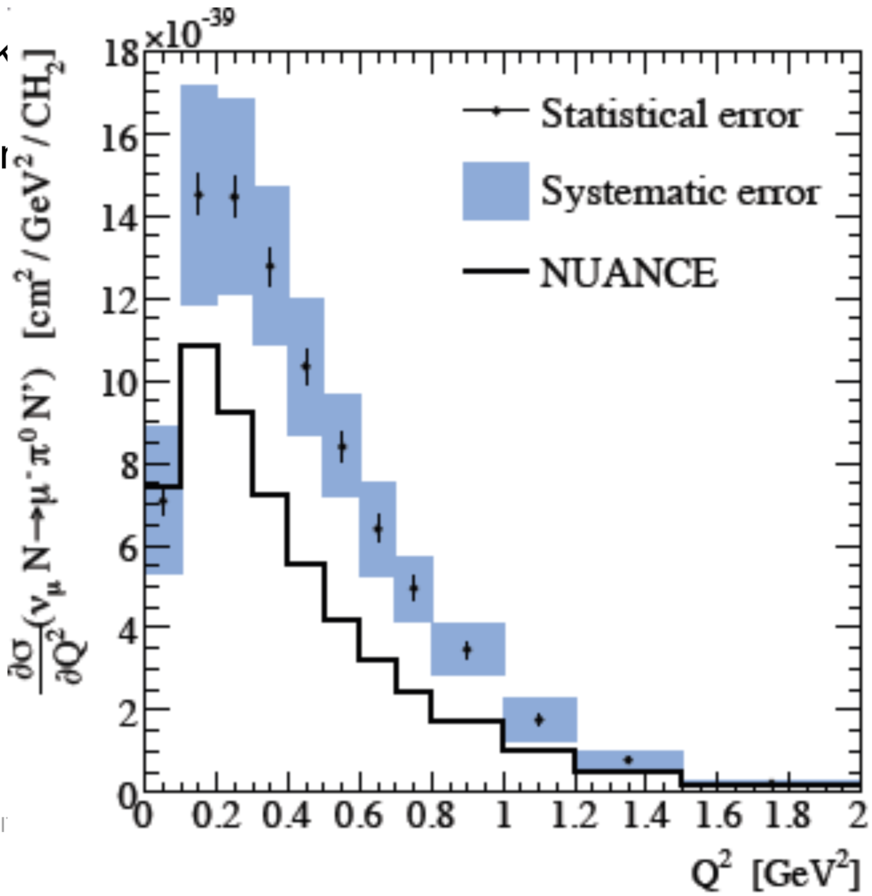
CCπº event

- There is no coherent contribution.
- There are only ~5% total and swamped by other CC channels.

CCπº differential cross section

- invariant mass of 2 gammas show πº mass peak
- Muon ID rate is >80% at πº mass peak.
- data is higher than Rein-Sehgal model prediction (M_A=1.1GeV) over 50%





0-6. Improved CCπ^+ simulation

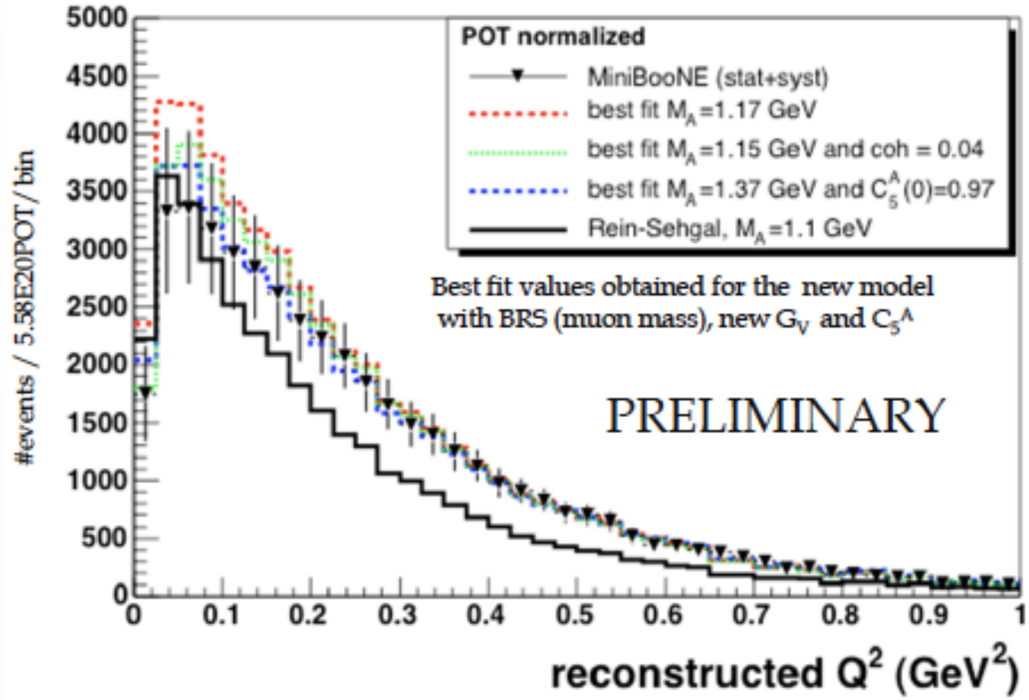
by Jarek Novak

Improved CCπ^+ prediction

All recent improvements are integrated in MiniBooNE simulation, including,
- muon mass correction,
- state-of-arts form factors

$M_A^{1\pi}$ fit with Q^2 distribution

The 3 different fits in Q^2 are performed,
1. $M_A^{1\pi}$ fit with Q^2>0.2
2. $M_A^{1\pi}$-coherent fraction simultaneous fit
3. $M_A^{1\pi}$-$C_A^5(0)$ simultaneous fit



0-7. $CC\pi^+$/CCQE cross section ratio

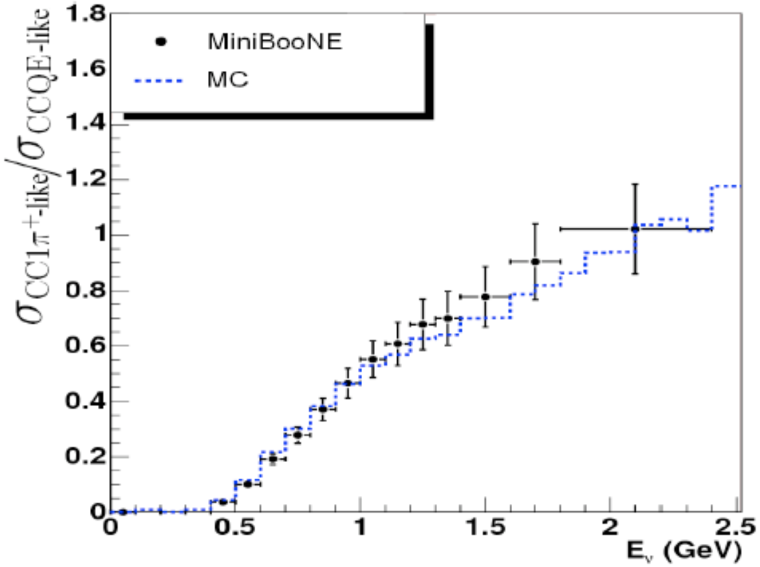
by Steve Linden

$CC\pi^+$/CCQE cross section ratio measurement

MiniBooNE collaboration,
PRL103(2009)081801

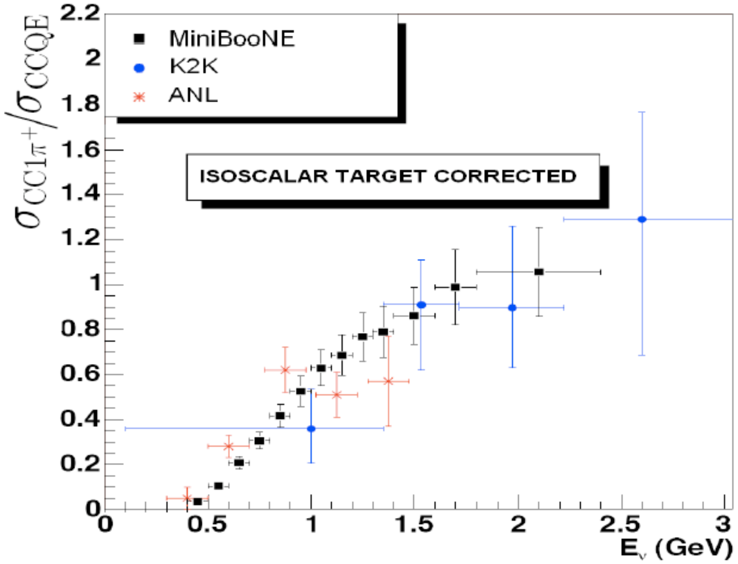
There is a complication for systematic error analysis, because
CCQE is the background in $CC\pi^+$ sample, and $CC\pi^+$ is the background in CCQE sample.
As is same with other pion production analysis, we emphasize that the FSIs are not corrected. We corrected it only when we want to compare with other experimental data.

$CC\pi^+$like/CCQElike cross section ratio



→

$CC\pi^+$/CCQE cross section ratio



by Joe Grange

MiniBooNE collaboration, paper in preparation

0-8. anti-νCCQE measurement

$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$

$$\left(\begin{array}{c} \bar{\nu}_\mu + {}^{12}C \rightarrow X + \mu^+ \\ \bar{\nu}_\mu + {}^{1}H \rightarrow n + \mu^+ \end{array} \right)$$

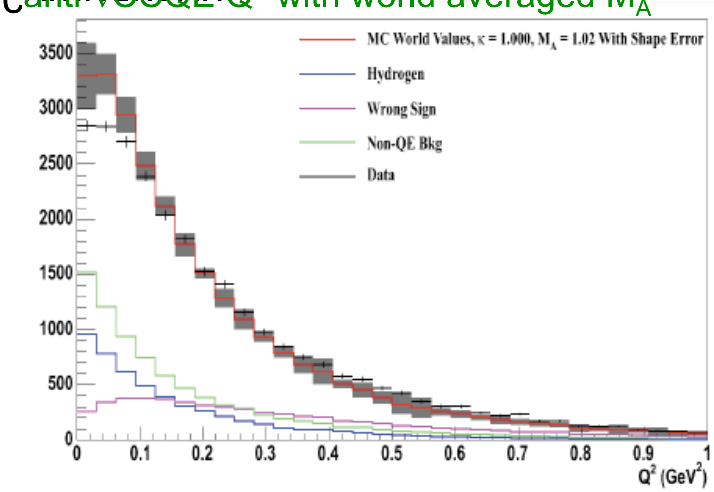
anti-νCCQE measurement is more complicated!

Comparing with νCCQE, anti-νCCQE measurement is more difficult,

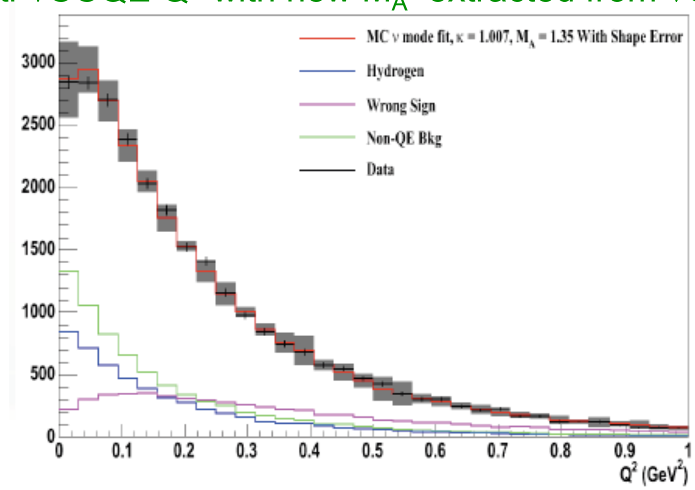
1. lower cross section
2. lower neutrino flux
3. higher wrong sign background
4. hydrogen scattering
5. no data-based CCπ background tuning is possible (nuclear π^- capture)

The preliminary result also support high M_A value in data-MC Q^2 shape-only c

anti-νCCQE Q^2 with world averaged M_A



anti-νCCQE Q^2 with new M_A extracted from νCCQE



0-9. NuInt09 conclusions

All talks proceedings are available on online (open access),
http://proceedings.aip.org/proceedings/confproceed/1189.jsp

Some realizations from NuInt09

1. Neutrino cross section measurements are the urgent program, mainly, because of their relationship with neutrino oscillation measurements.
2. Importance to use the better models for neutrino interaction generators
3. Importance to provide data with the form available for theorists, this includes,
   i) detector efficiency is corrected
   ii) free from reconstruction biases (data as a function of measured quantities)
   iii) free from model dependent background subtraction

e.g.) MC comparison of double differential cross section of NCπ^o production with Eν=0.5GeV, angle=60^o